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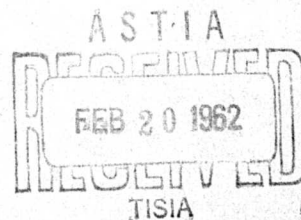# AN EXPERIMENTAL AIRBORNE 50 MCPS IONOSPHERIC SCATTER COMMUNICATION CIRCUIT

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October 1961

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Abstract

A two-way VHF air-ground-air ionospheric scatter communications experiment is described. The data, consisting of field strength measurements and baud error counts, indicate that an airborne teletype system using this mode of propagation is feasible to distances of approximately 1200 statute miles with known techniques and available equipment. Information is presented concerning the variation of the baud error rate with the number of diversity branches. The system performance during operation across the auroral zone at times of magnetic disturbances is discussed. Recommendations are made from which an operational system could be developed.

Acknowledgments

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For many years there has been a need for reliable long distance air-ground communication. This need has been felt most on long overseas flights and when communication between aircraft and ground bases must be maintained across the "auroral belt" where conventional high frequency propagation is often seriously disrupted.

UHF air-ground voice communications, utilizing the tropospheric scatter mode of propagation, could be extended by perhaps as much as 200 to 300 miles beyond the radio horizon. HF propagation, while greatly extending the communication range, exhibits extreme unreliability and provides a limited available spectrum. One possible approach is a VHF communication circuit designed to utilize the ionospheric scatter mode of propagation. Such a circuit would provide for low data-rate, single frequency operation at all ranges up to about 1500 statute miles.

This report will describe an experimental, two-way, air-ground-air VHF ionospheric scatter communication circuit capable of supporting a single 60 wpm simplex teletype channel. The experimental data that have been collected will be discussed and parameters for an effective operational link will be suggested.

1. Background

Early in 1957, the Communication Sciences Laboratory of the Air Force Cambridge Research Center became interested in the possibility of using the continuous VHF ionospheric scatter mode of propagation for long-distance air-ground communications. The literature at that time[1] contained many reports indicating that the continuous ionospheric scatter mode of propagation was highly reliable, even under conditions when conventional high frequency circuits would have been plagued with absorption difficulties resulting in radio "blackouts" for extended periods of time. In view of this, it was hoped that the techniques employed in the design of the successful point-to-point ionospheric scatter circuits could be extended, perhaps with some modifications, to the design of a highly reliable long-distance air-ground circuit.

The published data in 1957 did not give a conclusive picture of distance dependence (especially at extreme distances), height depend- ence, or the characteristics of the signal in the transition region between the tropospheric scatter and ionospheric scatter fields. In addition it had not been conclusively demonstrated that low gain antennas were as good as high gain antennas at low signal levels. Early in 1957 an experiment was undertaken jointly by AFCRC and Lincoln Laboratory[2] to study these and other characteristics of the medium. The path loss data obtained early in the experiment, combined with data from the literature, figured importantly in the circuit design calculations. From the AFCRC-Lincoln data it was estimated that at 1400 statute miles from the transmitter, at a receiver altitude of 35,000 feet, and with wide-beam antennas, the median path loss* should not exceed 220 db for 99 percent of the time.

One of the significant features of point-to-point ionospheric scatter circuits existing in 1957 was the use of large, narrow beam antennas, which obviously cannot be used on an aircraft. Relative to this problem, published experimental data[3] was available which compared the perform- ance of yagi and rhombic antennas under the same conditions. From those data it was estimated that during low signal periods the strength of the signal received on the rhombic did not exceed that received on the yagi by more than 2 or 3 db. Since the design for reliable circuit performance would eventually be based on low signal periods, it was concluded that for low data rate ionospheric scatter circuits where multipath effects are not a

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* "Path loss" is defined by the expression:

$$L_p = P_t + G_t + G_r - P_r$$

where:

  L_p = The path loss, in db, between the transmitter antenna and the receiver antenna.

  P_t = The transmitter power output, in db, relative to a watt.

  G_t = The plane wave free space gain, in db above isotropic, of the transmitting antenna.

  G_r = The plane wave free space gain, in db above isotropic, of the receiving antenna.

  P_r = The received power, in dbw at the input terminals of the receiver.

serious problem, the broad beam antennas could be substituted for the large rhombics or for other types of narrow beam antennas without unduly affecting the long time circuit reliability.

Once wide beam antennas had been accepted and since, based on previous laboratory experience[2], it was known that broad beam antennas having modest gains could be installed on an aircraft, it appeared that the design of a successful long-distance, ionospheric scatter air-ground communication circuit was well within the realm of possibility. Accordingly, late in 1957, a study and experimental program was established by the Communication Sciences Laboratory, AFCRC, to demonstrate the feasibility of a reliable two-way long-distance (0-1500 statute miles), 50 Mcps ionospheric scatter air-ground communication circuit. This circuit was to support a single, 60 wpm, Simplex teletypewriter link.

To provide for the most rigorous testing, the experimental work was conducted over a 1500 statute mile flight path between Bedford, Massachusetts and Frobisher Bay, Canada (see Fig. 1). This path was selected because it would operate across the auroral belt where intense absorption and radio "blackouts" often occurred at lower frequencies.

An operating frequency of 49.62 Mcps was chosen. The most useful frequency range for ionospheric scatter propagation appeared to be between 40 and 70 Mcps; availability of equipment and frequency allocations specified the choice within this range.

For the same reasons discussed in connection with the airborne antenna, it was believed that efficient antenna-to-medium coupling could be achieved with a wide horizontal beamwidth (approximately 45°) of the ground antennas because of the large variation in azimuth of the angle of arrival over a diurnal cycle. Desired gain was then to be realized by compression of vertical beamwidths.

Frequency shift keying was used because this method of modulation was of proven merit on fluctuating circuits where digital information only is to be transmitted. A frequency shift of 6 kcps was sufficient to overcome problems associated with meteoric Doppler shifts. Baud synchronous quasi-matched-filter detection was selected on the basis of an expected moderate improvement over broader-band methods of detection.

It was well known that ionospheric scatter signals are subject to deep fading. (To a first order approximation, it was expected that on a short term basis the signal amplitudes would be Rayleigh distributed[4,5].) To
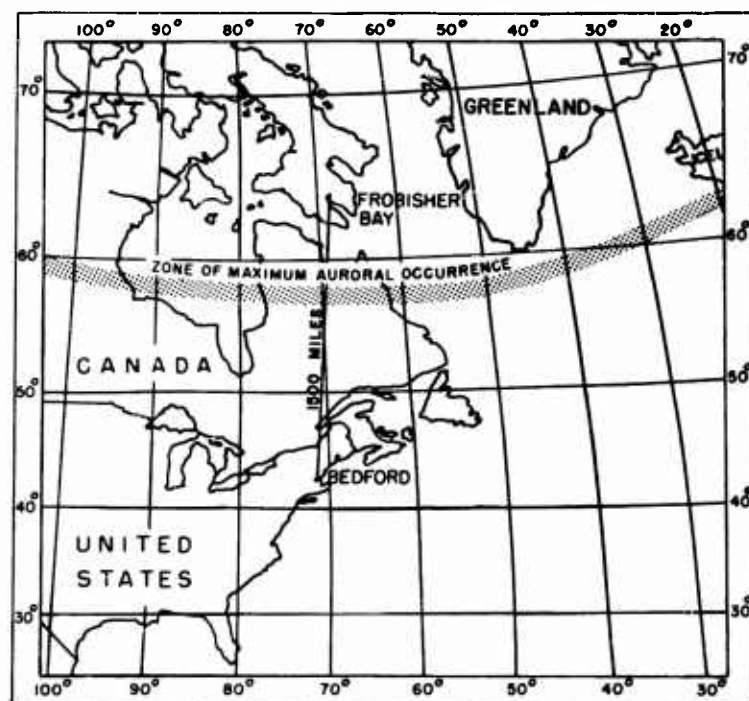
Figure 1. Flight Path

realize acceptable error rates in the presence of such fluctuations without using unduly high transmitter powers, some form of diversity reception was indicated. On the aircraft, use of space diversity was limited by sheer size considerations; a combination of dual space diversity (wingtip mounted antennas) and triple frequency diversity was ultimately selected for the ground-to-air transmission. The choice was made by comparing limits on other system parameters (transmitter power, noise level, path loss, etc.) with theoretically predicted error rates given by Pierce.[6] (The frequency diversity was realized by a frequency hopping technique, described in greater detail in Appendix A, rather than by simultaneous transmission on the diversity frequencies because of transmitter peak power limitations.) At the ground receiving site a six-fold diversity receiving system was decided upon, based again on practical considerations and theoretically predicted error rates.

Complete independence of signal fading on the several diversity branches of the airborne receiver could not be achieved because the limited separation between wingtips would prevent the signals on the spaced antennas from fading independently; reasonable spectrum occupancy prohibited independence of the fading on diversity branches separated in frequency. Theoretical predictions by Staras[7] and Pierce[6], however, suggested that the moderate degree of correlation caused by these limited separations would not cause appreciable degradation. On the ground the slight potential improvement to be gained by greater independence of fading was sacrificed to achieve sensible physical separation of the six antennas.

At the outset of the project no equipment of any kind was on hand, and no "off the shelf" items were suitable for use as building blocks. Practically all essential items had to be designed, developed, and produced either by laboratory personnel or by commercial concerns.

While a transmitting site with most of the essential features was available at Prospect Hill, Waltham, Massachusetts, no receiving site of any kind existed. After considerable investigation of the surrounding terrain, a receiving site was established at Oak Hill, Littleton, Massachusetts.

Between November 1958, and June 1959, while some essential equipment had still not been delivered, important field work was done of field strength measurement, antenna measurements, aircraft electrical noise investigations, and the refinement of circuit performance measurement techniques. Final project tests were begun in November 1959, and were completed May 1961.

2. Description of Equipment and Experimental Techniques

Equipment

The desired result from the flight test program was a complete determination of system performance, including the distance dependence of field strength, error rates and the efficiency of the receiver and diversity techniques used. The essential parameters describing the experiment are summarized in Table 1. Both the ground-to-air and air-to-ground channels operated on a center frequency of 49.62 Mcps, used FSK modulation, employed diversity techniques to improve the error rate and had relatively broad beam antennas for both transmitting and receiving. The airborne terminal equipment was installed in an Air Force KC-135 jet tanker aircraft. With this aircraft the experiment could be conducted under conditions closely approximating those found in other high speed operational aircraft while sufficient space and electrical power for the experimental equipment was provided.

The ground-to-air channel operated with a transmitted power of 45 kw. The transmitting antenna had a free space gain of 15 db above isotropic and the airborne receiving antenna had a free space gain of 7 db. Three-fold frequency diversity was employed with a 30-kcps diversity spacing. The FSK spacing was 6 kcps. The baud length was 30 milliseconds; each baud was transmitted on each of the three diversity frequencies in turn for 10 milliseconds. The airborne and ground receivers both used baud synchronous detection with matched filters for maximum sensitivity. Diversity combination was post detection maximum signal selection. The aircraft receiving system as originally designed also employed dual space diversity utilizing antennas installed on the wingtips. Unexpected precipitation and engine charging static rendered these antennas useless (see Appendix B). This interference did not appear on the nose and tail antennas, which were successfully used for both receiving and transmitting purposes.

The air-to-ground channel operated with transmitter power of 5 kw and with an airborne transmitting antenna free space gain of 7 db. Six space diversity receiving antennas with free space gains of 12 db each were used on the ground. The horizontal beamwidths of all antennas were between 45° and 60°. Modulation was FSK with a frequency spacing of 6 kcps and a baud length of 30 milliseconds. The detection and diversity combination were identical to the ground-to-air channel. The ground receivers also had a channel utilizing only narrow filters (FSK-3 receiving system) enabling a comparison between this and the matched filter (FSK-4) channel. Appendix A contains a detailed description of the equipment used for this experiment. The air-to-

TABLE 1

SUMMARY OF SYSTEM PARAMETERS

	Ground-to-Air Channel	Air-to-Ground Channel
Center Frequency	49.62 Mcps	49.62 Mcps
Transmitted Power	45 kw	5 kw
Free Space Gain - Transmitting Antenna	17 db (Dipole Array)	7 db (Nose or Tail Antenna)
Free Space Gain - Receiving Antenna	7 db (Nose or Tail Antenna)	12 db (Two Stacked Yagis)
Antenna Horizontal Beamwidths	Between 45° and 60° for All Antennas	Between 45° and 60° for All Antennas
Path Length	From 0 to 1500 Statute Miles	From 0 to 1500 Statute Miles
Diversity	3 Frequency, spacing = 30 kcps	6 Space, spacing = 163 ft Normal to Path
Modulation	FSK - Spacing 6 kcps on Each Diversity Frequency	FSK - Spacing 6 kcps
Baud Length	30 ms, 10 ms on Each Frequency	30 ms
Filtering (Detection)	Baud Synchronous with Matched Filters (FSK-4)	Baud Synchronous with Matched Filters (FSK-4), Narrow Filters (FSK-3)
Diversity Combining Method	Post Detection Maximum Signal Selection	Post Detection Maximum Signal Selection
Noise Bandwidth - Field Strength Channel	400 cps	400 cps
Field Strength Recorder Time Constant	0.5 sec	0.5 sec
AGC Time Constant	0.1 sec	0.1 sec

ground channel design called for a transmitter power of 10 kw, but due to transmitting antenna arcing and corona at operating altitude the power was restricted to 5 kw. Sixty-wpm synchronous teletype terminal equipment was designed and constructed but was not used as a basis in determining baud error rates.

The ground transmitter was located on Prospect Hill, Waltham, Massachusetts. Figure 2 is a photograph of the antenna and transmitter building. The ground receiving terminal was located on Oak Hill, Littleton, Massachusetts, about 20 miles west of Bedford.

Experimental Techniques

The experimental techniques for the operation of the ground-to-air and air-to-ground channels were almost identical. Transmissions consisted of continuous alternate mark space information, interrupted every five minutes for a 30-second period when the transmitter was shut off for identification and a noise level check. The diversity combiner output was fed into an error detector which compared the received sequence with a locally generated alternate mark-space signal to determine the occurrence of baud errors. In the aircraft the errors were recorded in alternate ten second intervals using a Hewlett-Packard frequency counter as the readout device. On the ground the errors were recorded continuously using mechanical readout devices. Continuous field strength data were obtained on an Esterline-Angus pen recorder. The ground receiver was equipped with two diversity combiners in parallel, allowing the simultaneous measurement of baud error rates for two separate orders of diversity.

Data were obtained on both outbound and inbound flight legs. The average round trip time was 6-1/2 hours. The flight altitude varied between 33,000 and 37,000 feet. Ground-to-air measurements were made at various times of day to observe the effects of propagation conditions during different parts of the diurnal signal strength cycle. Because of daytime rf interference and ambient noise problems at the ground receiving site (See Appendix C), air-to-ground measurements were all made between 10 P.M. local time and sunrise.
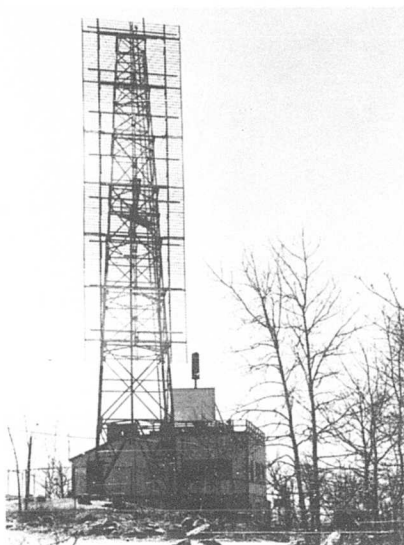
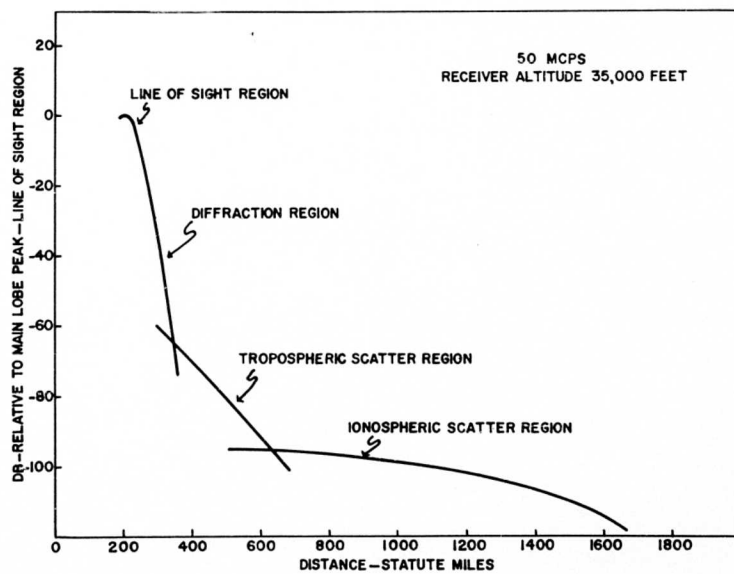Figure 2. Ground Transmitting Antenna and
Transmitter Building

Figure 3. Idealized Distance Decay Curve

3. Experimental Results

Introduction

Successful flights evaluating the scatter communications system were made from fall 1959 until spring 1961. The results consisted of field strength data and baud error rates for both the air-to-ground and ground-to-air channels. The air-to-ground channel provided information on the improvement in the error rate with increasing orders of diversity. Flights were made during periods of considerable auroral activity, enabling the evaluation of the system operation at times of poor HF radio reception.

The distance dependence of the field strengths at 50 Mcps has been investigated and reported on in previous reports[2], but a review of the more important features is in order. Referring to the idealized distance dependence curve (Fig. 3), the first regions encountered as the receiver is moved away from the transmitter are the line-of-sight and diffraction zones. The very sharp decay curve of the diffraction zone continues until the tropospheric scatter mode of propagation appears. For a receiver altitude of 35,000 feet this occurs at a distance of about 300 to 350 statute miles. The tropospheric scatter signal is characterized by a distance decay of the order of 15 db per 100 miles for a receiver altitude of 35,000 feet.

At distances from 500 to 700 miles the transition to the ionospheric scatter mode of propagation takes place. Ionospheric scatter propagation is characterized by very weak field strengths, the presence of rapid fading and meteoric reflections in the signal and a fairly flat distance decay rate of the order of 2-4 db per hundred miles out to that distance where the scattering region is obscured by the bulge of the earth. Assuming a scattering layer at a height of 85 km, the scattering medium should be visible at the receiver altitude mentioned to distances of the order of 1600 statute miles. The median path loss found in the ionospheric scatter region at this frequency varies between 210 and 240 db, depending on distance, path chosen, time of day and time of year.

Ground-To-Air Data

The field strength data were reduced from the Esterline-Angus recorder charts in the form of one-minute median levels. Although the recorder signal was derived after the frequency diversity combination, it is felt that the

median of this combined signal does not differ significantly from that which would have existed if a single frequency signal had been recorded. Figure 4 is the combined ground-to-air field strength data plotted at ranges of 800, 1000, 1200 and 1400 statute miles. In general there are two data points plotted at each distance for each flight, one outbound and one inbound leg. Data obtained at different times of the day are indicated. Note that the day-to-day variation in signal level masks any diurnal variation. The field strength during the period from 1600 to 2100 hours appears weaker by a few db than that measured in the mid-day and mid-night hours. Figures 5 and 6 are the plots of data obtained on two representative flight legs.

Baud errors were obtained in one-minute samples and tabulated against the median signal-to-noise ratio (recorded in a channel with a noise bandwidth of 400 cps). Figure 7 is a summary of the compiled ground-to-air, three-frequency diversity baud error data. Only ionospheric scatter data are included. For each value of signal-to-noise ratio, the figure shows the number of one minute baud error samples obtained at that level, the percentage of the samples without error, the percentage of the samples with a baud error rate of 0.1% (1 error per 1000-baud sample) the percentage of samples with an error rate of 0.2% or 0.3% (2 or 3 errors per 1000-baud sample) and the percentage where the error rate is greater than 0.3% (greater than 3 errors per 1000-baud sample). For 60 word-per-minute, 75 character-per-line synchronous teletype, one character error per line of copy corresponds to a baud error rate of 0.27% if baud errors occur randomly. (Since the fading rate is such that there is a tendency for clustering of errors, a specified character error rate might actually be obtained at slightly higher baud error rates.) Note that for the ground-to-air case only half of the bauds in each minute (1000 out of 2000) were used to determine the error rate.

Although the error count is compiled as a function of signal-to-noise ratio, the signal character also exerts considerable influence on the error rate. Consider Figs. 8 and 9, signal samples taken during flights 21 days apart, but at the same time of day, at about the same distance and under identical experimental conditions. The signal of Fig. 9, because of the greater median-to-trough ratio of the fading, would begin producing errors at a median signal level about 5 db higher than that of Fig. 8. The two examples noted are extremes with most of the other data falling somewhat in between. The distribution of signal levels for these two samples, adjusted to equal median levels, is shown in Fig 10.
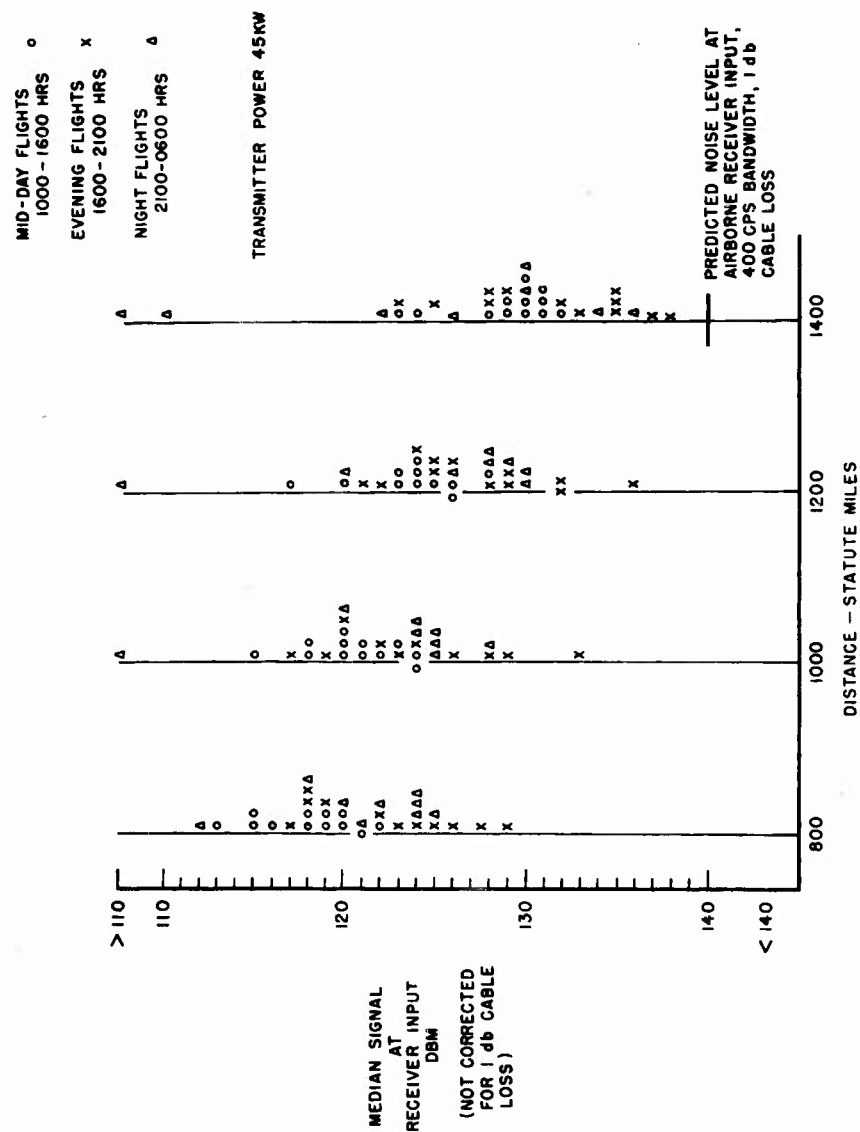
12

Figure 4. Combined Ground-to-Air Field Strength Data
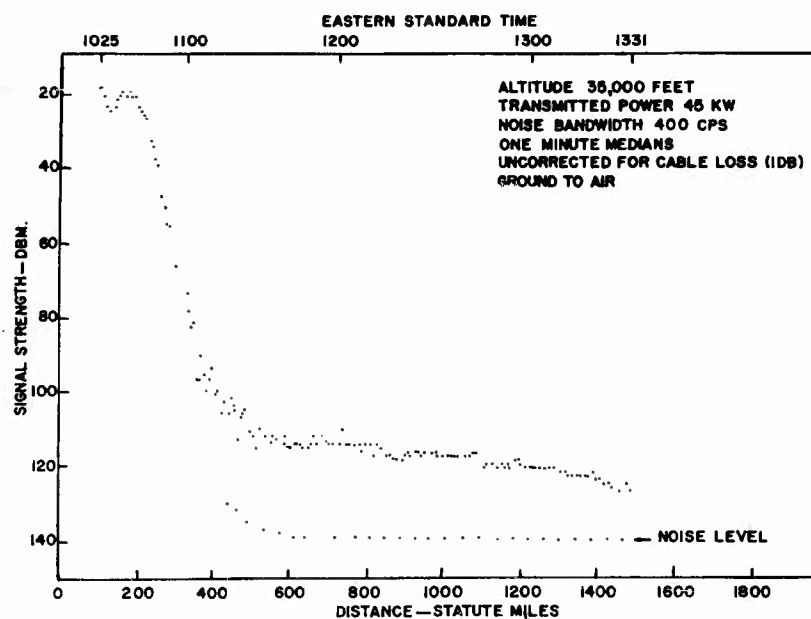(Sampled at 800, 1000, 1200 and 1400 Statute Miles)

Figure 5. Signal Level Curve - April 13, 1960 - Outbound Flight
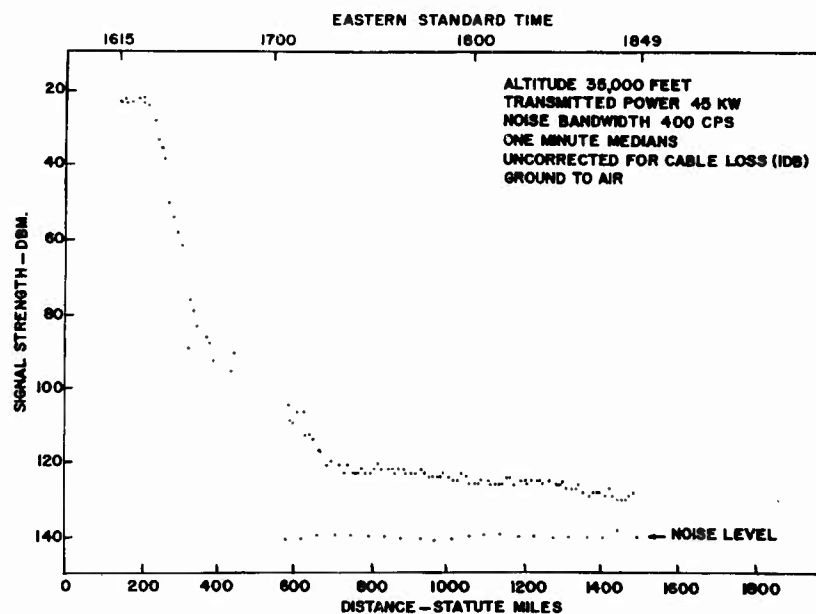
Figure 6. Signal Level Curve - May 2, 1960 - Outbound Flight

14
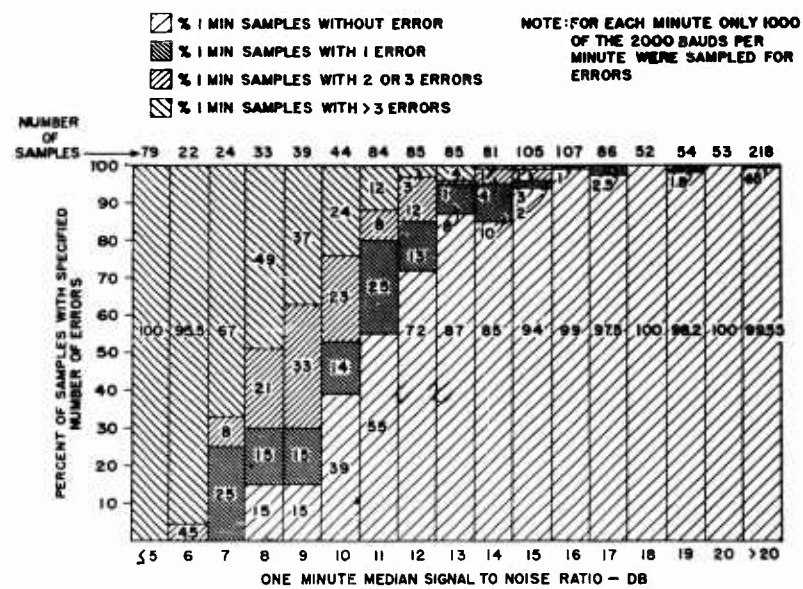
Figure 7. FSK-4 Baud Error Rate Data, 3
Frequency Diversity, Ground to Air
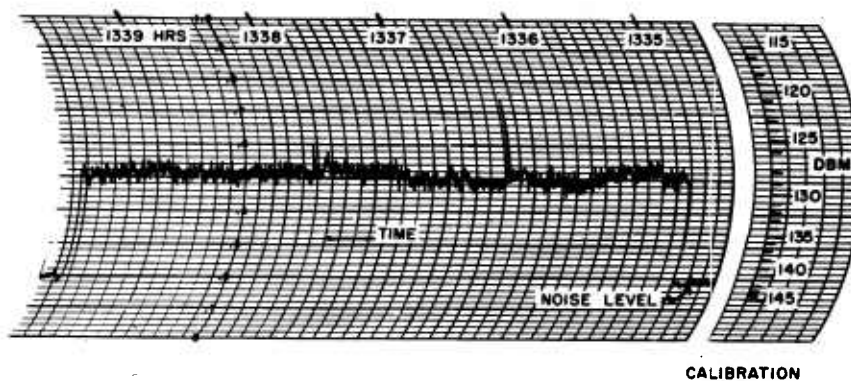
DISTANCE AT 1335 HRS. = 1448 STATUTE MILES
GROUND SPEED = 9 MILES / MINUTE
MEDIAN SIGNAL LEVEL = 129 DBM.
NOISE LEVEL = 142 DBM. (400 CPS BANDWIDTH) } S/N = 13 DB
MEDIAN SIGNAL / LOW SIGNAL = 2 DB

Figure 8. Received Signal For 1 April 1960 –
Ground/Air Flight
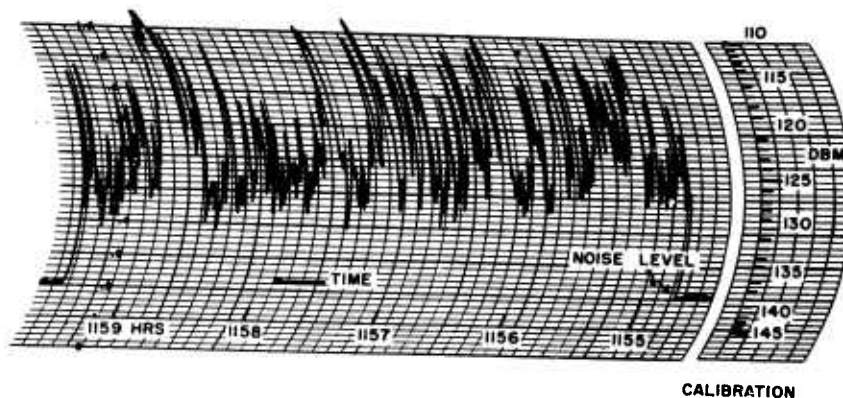
DISTANCE AT 1155 HRS. = 1300 STATUTE MILES
GROUND SPEED = 8 MILES / MINUTE
MEDIAN SIGNAL LEVEL = 124 DBM
NOISE LEVEL = 138 DBM. (400 CPS BANDWIDTH) } S/N = 14 DB
MEDIAN SIGNAL / LOW SIGNAL = 7 DB

Figure 9. Received Signal For 22 April 1960 –
Ground/Air Flight

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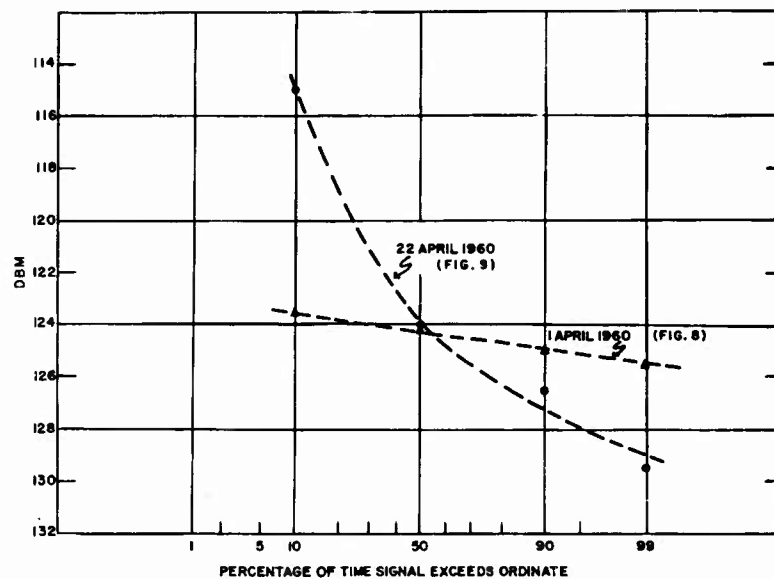
Figure 10. Comparison of Signal Level Distributions of 5
Minute Data Samples of Figures 8 and 9.
Curves Normalized at 50% Level

Air-To-Ground Data

The air-to-ground field strength data were obtained from one of the six space diversity receivers, before diversity combination took place. The combined air-to-ground field strength data plotted at ranges of 800, 1000, 1200 and 1400 statute miles are shown in Fig. 11. Figures 12 and 13 are representative of the data obtained on individual flights.

The baud error data for the air-to-ground channel were reduced and compiled in the same manner as in the ground-to-air data. Figure 14 is a summary of the air-to-ground baud error rate measured using the six space diversity FSK-4 (baud synchronous, matched filter) receiving system. For each value of signal-to-noise ratio the number of samples, the percentage of samples without error, the percentage of samples with a baud error rate of from 0.15% to 0.25% (3 to 5 errors per 2000-baud sample) and the percentage of samples with a baud error rate greater than 0.25% (greater than 5 errors per 2000-baud sample) are shown. For the air-to-ground channel all of the transmitted bauds were used to determine the error rate. Figure 15 shows the baud error rate data obtained using the six space diversity FSK-3 (narrow filters only) receiving system. It is seen that the FSK-4 system provided considerable improvement over the FSK-3 system, especially at low error rates.

Diversity Studies

Using the air-to-ground FSK-4 space diversity system, measurements were made of baud error rates using 1 receiver, 2 receivers, 3 receivers and the already mentioned 6 receivers. These data were reduced, compiled and plotted as discussed in the section on "Ground-to-Air Data". Figure 16 shows the baud error rate for 3-diversity; Fig 17, 2-diversity; and Fig. 18 no diversity. Note the change in the horizontal (signal-to-noise ratio) scale with different orders of diversity. The increase in the error rate with decreasing order of diversity is clearly shown in these figures. The greatest improvement is observed in going from no diversity to two diversity operation. Enough gain is noted in going from 3 diversity to 6 diversity to warrant the use of the extra antennas and receivers involved.

Comparison of Figs. 7 and 16 shows that the error rates achieved with 3 frequency and 3 space diversity are very similar. The 3 space diversity data show a slight improvement over the frequency diversity case; this is due to the power splitting involved in frequency diversity. (See Appendix A, Detailed Description of Equipment, for complete details.)

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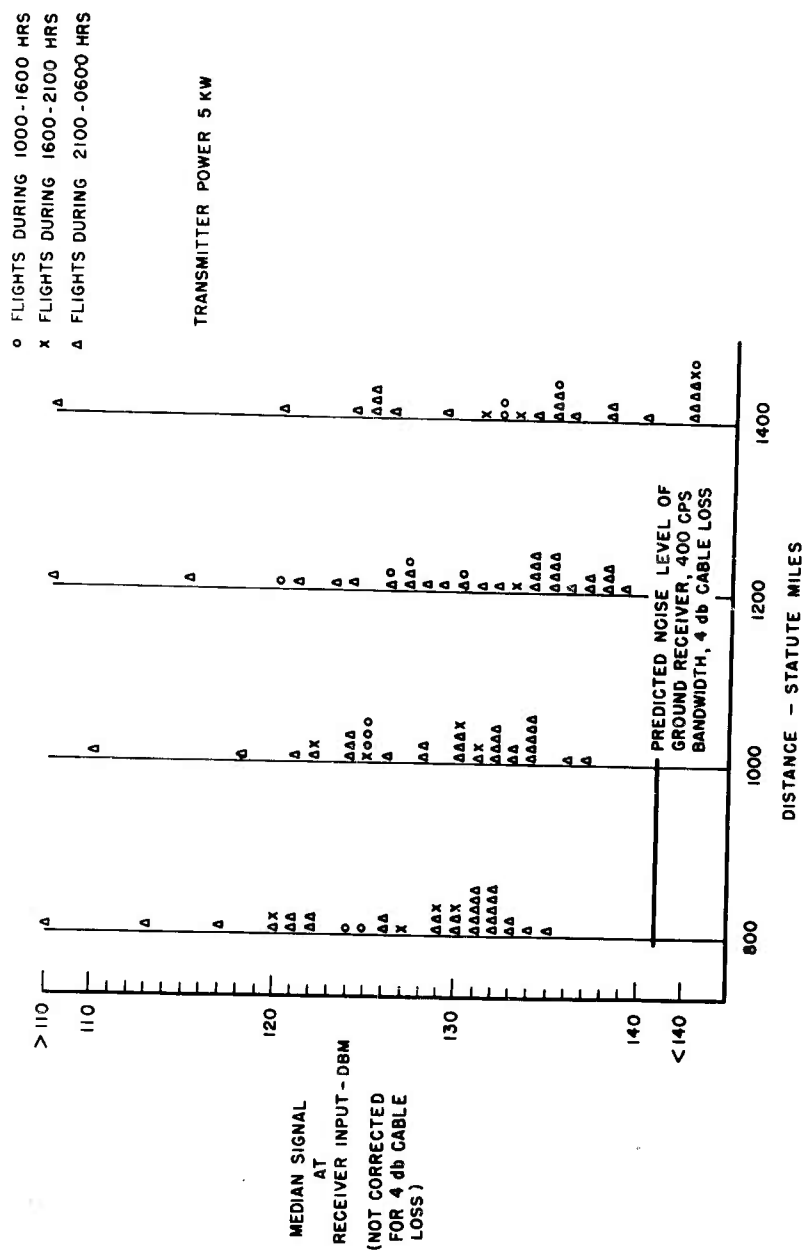
Figure 11. Combined Air to Ground Field Strength Data
(One Minute Medians Sampled at 800, 1000, 1200 and 1400 Statute Miles)
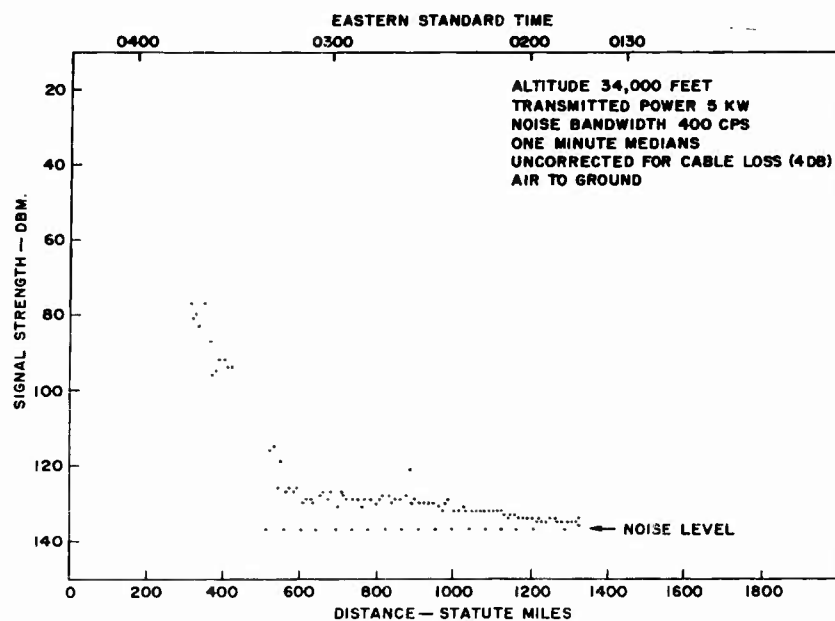
Figure 12. Signal Level Curve - 27 March 1961 - Inbound Flight
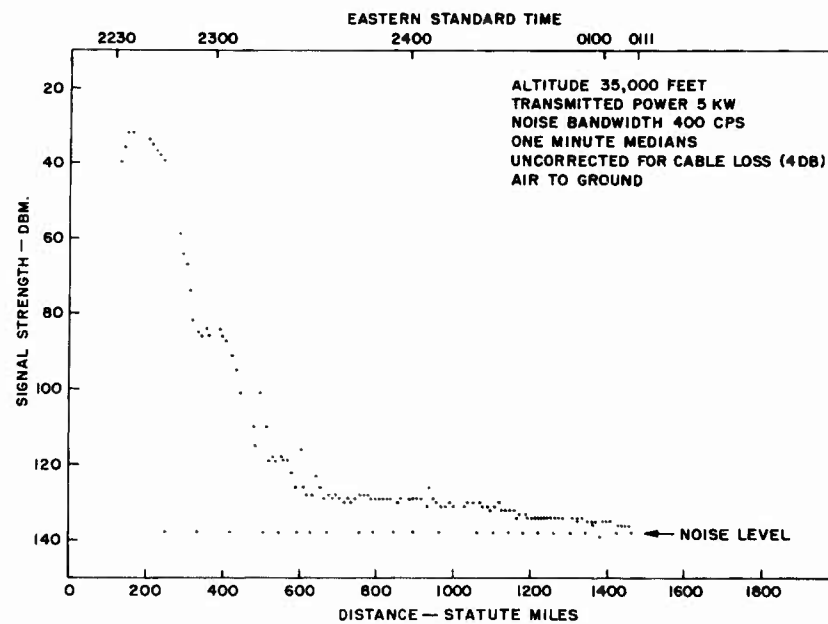
Figure 13. Signal Level Curve - 22-23 May 1961 - Outbound Flight
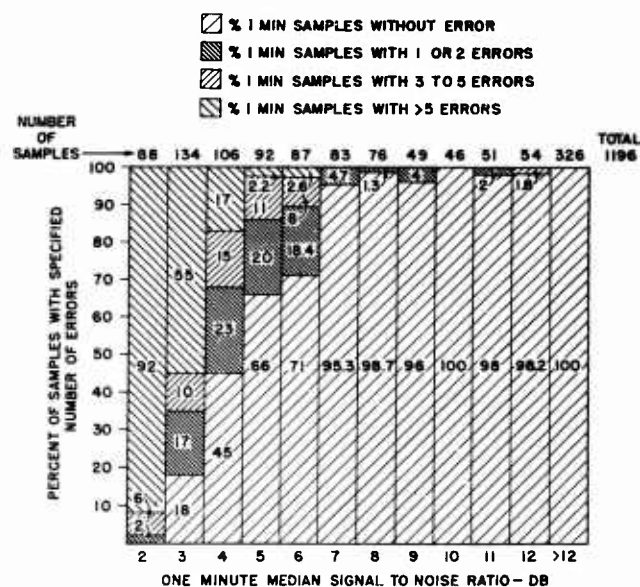
Figure 14. FSK-4 Baud Error Rate Data,
6 Space Diversity, Air to Ground
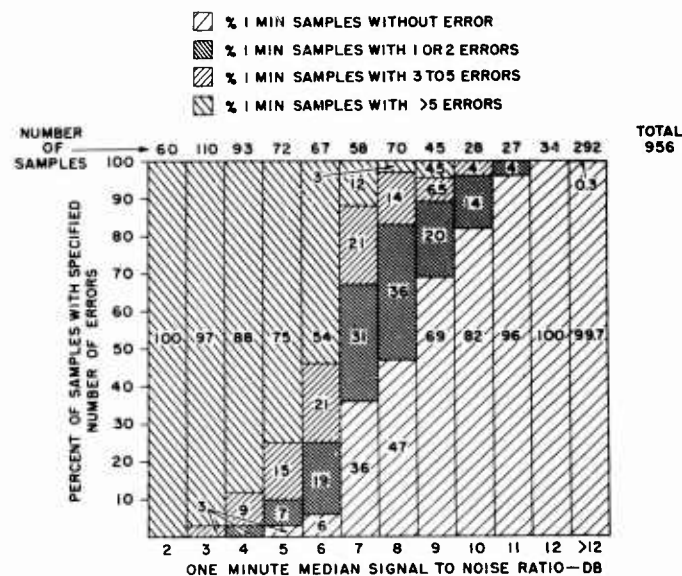
Figure 15. FSK-3 Baud Error Rate Data,
6 Space Diversity, Air to Ground
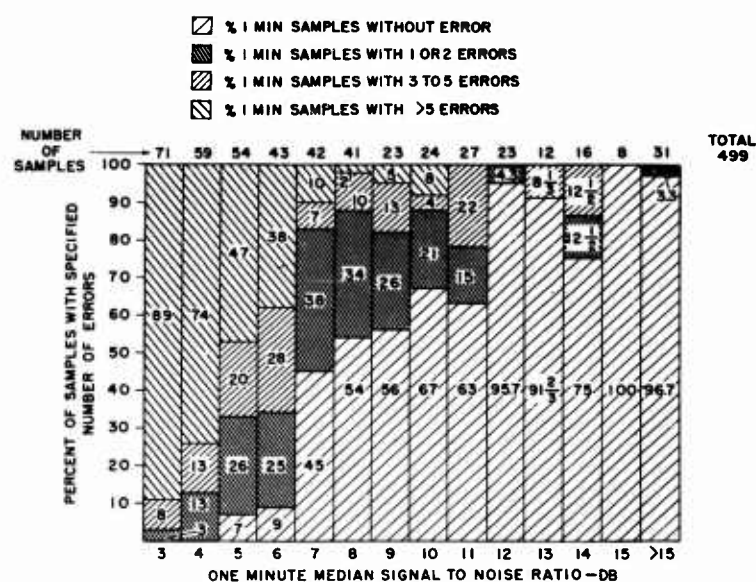
Figure 16. FSK-4 Baud Error Rate Data,
3 Space Diversity, Air to Ground
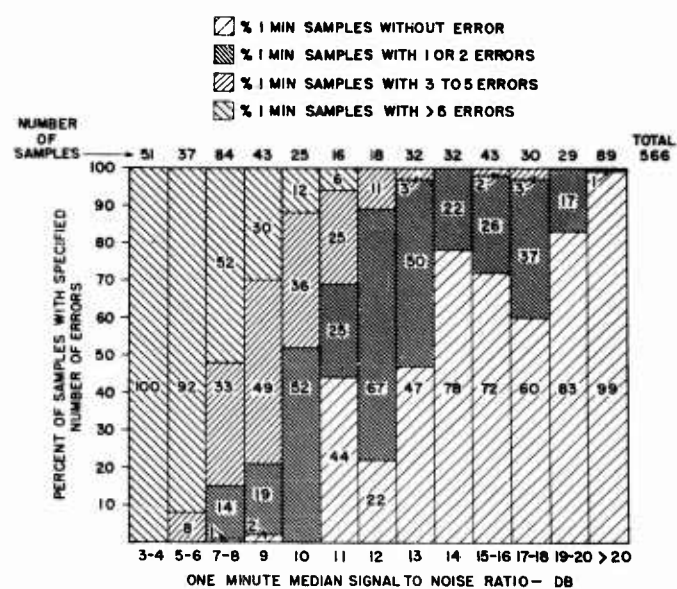
Figure 17. FSK-4 Baud Error Rate Data,
Dual Space Diversity, Air to Ground
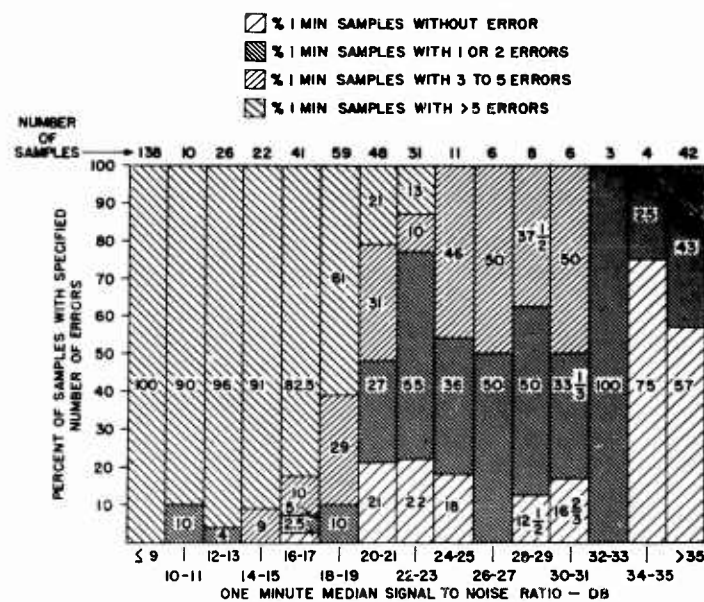
Figure 18. FSK-4 Baud Error Rate Data,
No Diversity, Air to Ground

Auroral Effects

About a third of the ground-to-air measurements and all of the air-to-ground measurements were made during hours of darkness. A close watch was maintained from the aircraft for any visual indications of aurora. Sightings were recorded in the flight log and noted on the signal level plot. At no time during auroral displays was unusual signal attenuation noted; in fact, all instances of nighttime signal enhancement were accompained by strong auroral activity during all or part of the flight leg. (A signal enhancement is defined as a prolonged increase of signal strength over that expected.) Instances of weak aurora without signal enhancements, and enhancements at dusk, when visual correlation with aurora was impossible, also occurred. During most of the brilliant auroral displays normal HF transmission from the aircraft was impossible.

A detailed examination of the data of two ground-to-air measurements is of interest at this point. As shown in the signal level charts of 29 April 1960 (Figs. 19 and 20), the lowest signal levels measured during the course of the experiment occurred on the outbound leg of this flight. Immediately after initiation of the inbound leg the signal began a gradual rise to a level 10-15 db above that of the outbound leg. Coincident with this enhancement, a strong aurora was noted over the aircraft at a distance of 900 miles and continued throughout most of the remainder of the flight. As far as could be determined experimental conditions and procedures were identical on both legs.

The flight made on the night of May 5-6, 1960 consisted of four complete passes through the region where only ionospheric scatter propagation was received. The first outbound leg (Fig. 21) exhibits a normal gradual decay curve. After turnaround, the signal (Fig. 22) appears to increase by about 5 db over the outbound leg at distances of 1000 and 1400 miles. Aurora was first noticed at 1000 miles and was present until 800 miles, the turnaround point for the second outbound leg. The second outbound leg (Fig. 23), while showing about 5 db less signal at 800 miles than the inbound leg, contains increases in signal level from 5 to 15 db over the first outbound leg. Note the difference in the character of the decay curve and the sudden enhancements. Moderate to strong auroral activity was present throughout this leg of the flight. The second inbound leg (Fig. 24) shows very strong enhancements, as much as 50 db from 900 to 1000 miles. Very strong auroral activity between the aircraft and the transmitter was noted at distances of 1500 and 1100 miles with moderate auroral activity present

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Figure 19.   Signal Level Curve - April 29, 1960 -
Outbound Flight

Figure 20.   Signal Level Curve - April 29, 1960
Inbound Flight

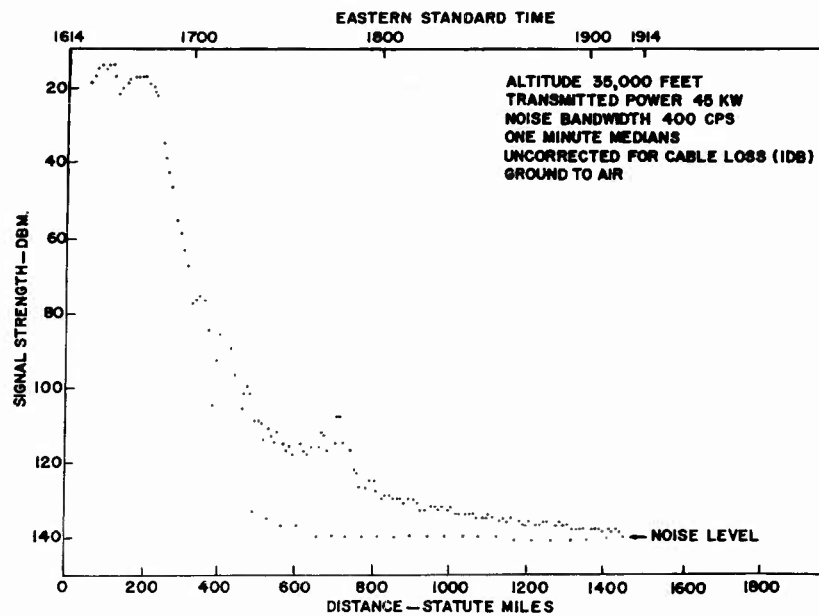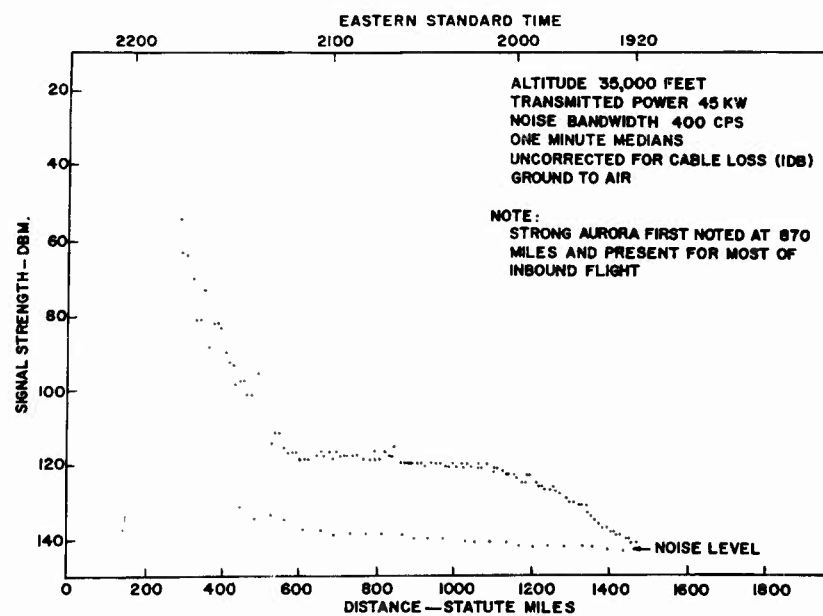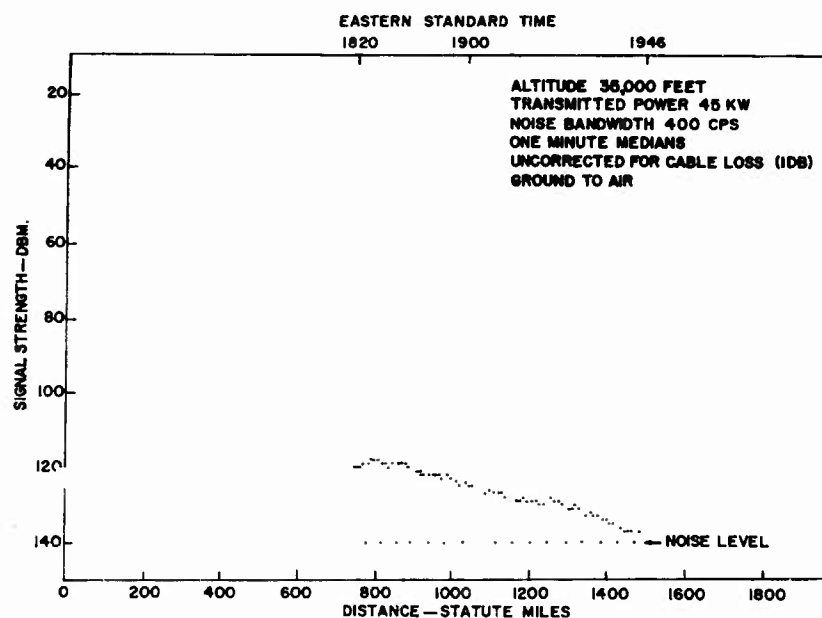Figure 21. Signal Level Curve - May 5-6, 1960 -
Outbound Flight #1
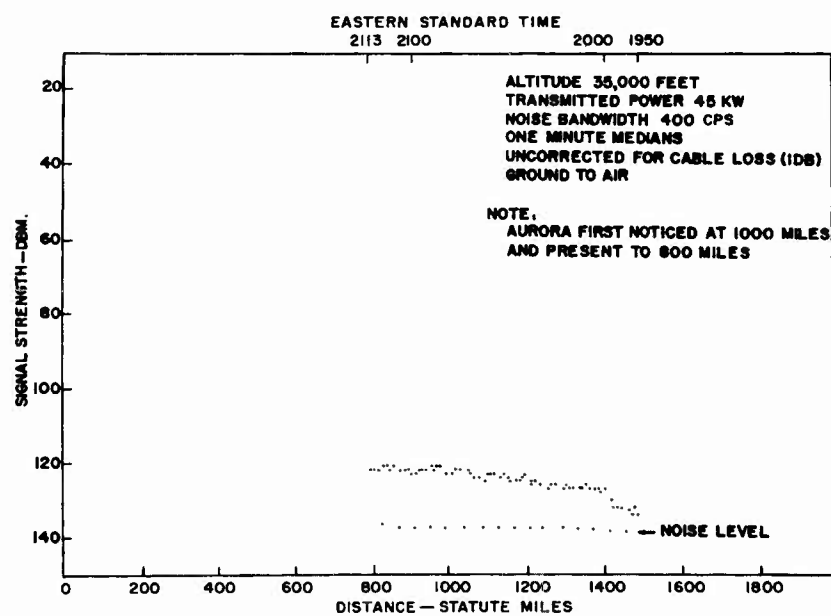
Figure 22. Signal Level Curve - May 5-6, 1960 -
Inbound Flight #1

Figure 23. Signal Level Curve - May 5-6, 1960 -
Outbound Flight #2
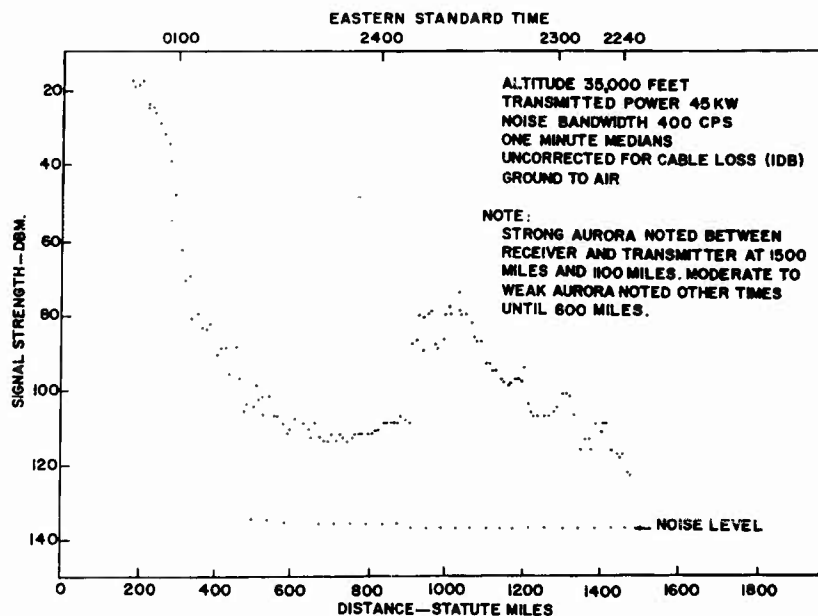
Figure 24. Signal Level Curve - May 5-6, 1960 -
Inbound Flight #2

until 600 miles. Figures 25 and 26 are the signal level charts of air-to-ground flights showing large enhancements coincidental with auroral displays.

Ground-to-air flights were made on April 1 and April 6, 1960, during a period of considerable magnetic disturbance. No abnormal attenuation in signal level was noted; in fact, the inbound leg of April 1 contains enhancements over signal levels observed on the outbound leg. The decrease in background noise levels on April 1 indicates possible absorption of cosmic noise. The signal sample of April 1, 1960 (Fig. 8) is interesting not only in the lack of deep fades but also in the absence of meteor activity. This sample is representative of all measurements made of the ionospheric scatter signal for that day. If a D-layer (height 80-85 km) scatter mechanism is postulated, the energy normally reflected from meteor trails occurring at upper E-region altitudes (90-120 km) could have been undergoing absorption in the region directly above that responsible for the background scatter signal.

4. Conclusions

This experiment demonstrates the feasibility of an air-ground-air teletype communications circuit utilizing VHF ionospheric scatter propagation. Distances up to 1500 statute miles (aircraft altitude greater than 30,000 feet) can be realized with a reduced data rate and greater system gain. The advantage of such a system is the reliability of the scatter mode. The primary limitations of this propagation mode are the high path loss necessitating low data rate per transmitted watt, and the severe short time fluctuations of the signal strength about its average value. Diversity techniques and baud-synchronous filtering are advised to minimize the error rate. A two-diversity receiving system seems to be a necessity, and from three to six orders of diversity are highly desirable.

For the ground-to-air link of an operational system, the AFCRL experimental parameters are considered to be a satisfactory choice for a successful 60-wpm teletype channel to distances of approximately 1200 statute miles. A successful channel is feasible to as much as 1500 miles if the overall system gain is increased. The system can be strengthened in the following areas:
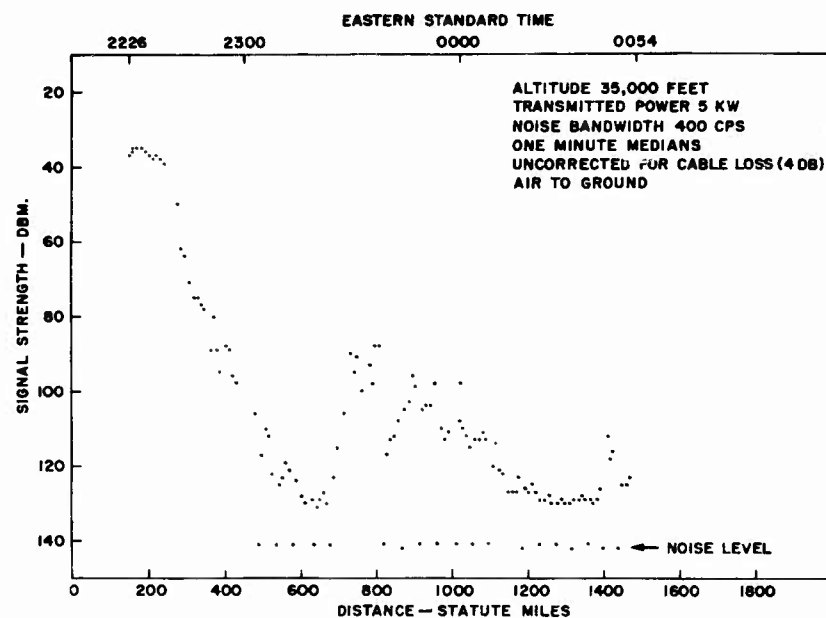
Figure 25. Signal Level Curve - May 15-16, 1961 -
Outbound Flight

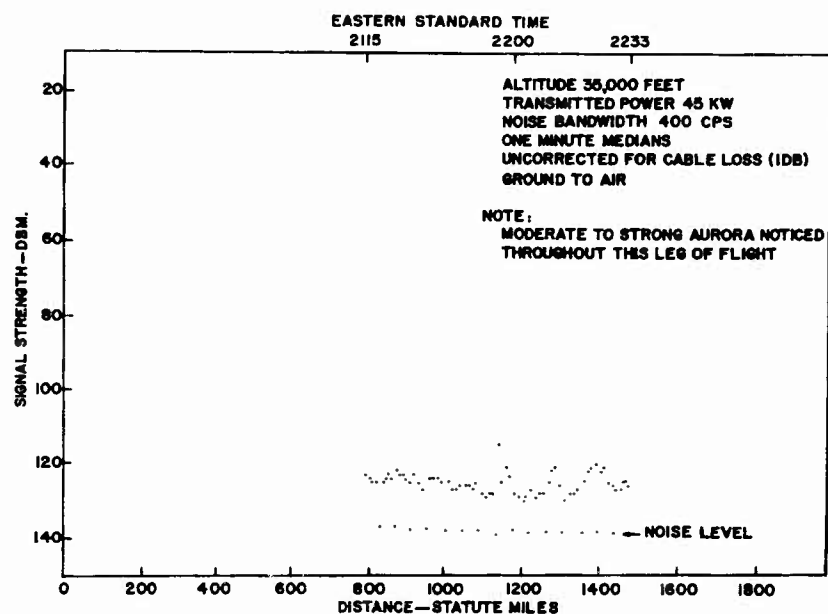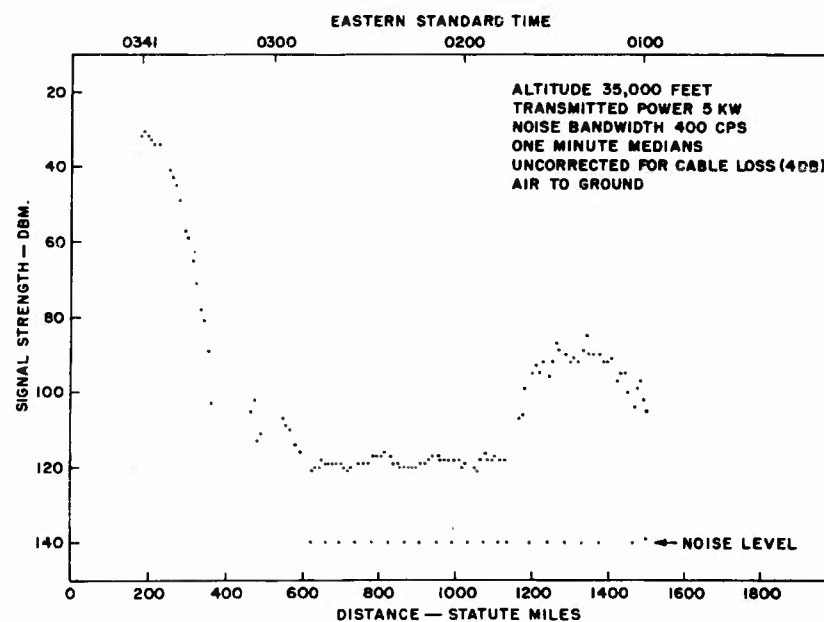Figure 26. Signal Level Curve - May 24-25, 1961 -
Inbound Flight

1) The addition of two orders of space diversity, giving a total of six orders of combined frequency and space diversity, would yield as much as 5 db improvement.

2) Transmitters with average power outputs as high as 500 kilowatts at this frequency are available.

3) An increase in the total antenna system gain is possible. It should be noted, however, that because of the nature of the scatter mechanism there are limitations on the improvement attainable by increasing antenna size.

The air-to-ground channel used for this experiment is adequate to about 1100 statute miles. Considerable improvement on this system, enabling successful 1400-mile operation, is possible. A limited redesign of the airborne transmitting antenna would permit the use of 10 kw of transmitted power (rather than the 5 kw used) at the airborne transmitting terminal. The airborne transmitter was operated in the air at 10 kw levels for short periods. It would be feasible to increase the ground antenna gain by about 8 db and to increase the airborne antenna gain slightly. Proper ground receiver placement involving a site with a low ambient noise level and smooth foreground would eliminate problems encountered by AFCRL at the Oak Hill receiving site.

In addition to the air-ground-air capabilities, an air-to-air communications circuit appears possible, especially if the range of operation is limited to 1100 miles. Much engineering would be required to obtain the transmitter power and antenna gains required. A 60-wpm teletype channel would require 3 to 6 orders of diversity, transmitter power of the order of 20 kw and antenna gains of 10 db for both transmitting and receiving aircraft.

Appendix A
Description of Equipment
M. Burak, J. Short, J. Frazier

GROUND RECEIVING STATION
Physical Description of Site

The Oak Hill facility had six two-bay, six-element Yagi antennas mounted on 71-ft towers spaced 223.5 ft apart and pointed 2° east of north. The antenna spacing normal to the direction of the received waves was 163 ft, or about eight wavelengths at 49.62 Mcps. Three types of transmission lines used produced approximately equal attenuation from a tower base to a receiver. The maximum attenuation measured was 3.2 db and the minimum, 2.3 db.

The six receivers and auxiliary equipment were housed in two trailers; a third trailer was used for spare parts and test equipment storage. A modified house trailer provided a workshop and accommodations for the operating personnel.

The antenna in the trailer area was rotatable and used for general monitoring purposes. Temperature control in the trailers proved troublesome, with ambients ranging from 40° to over 100° F. Commercial power was usually used, but a 25 kw diesel generator was available for emergency purposes.

The antennas employed at the receiving site were horizontally polarized, six-element Yagis (Telrex Model 6M) in two-bay vertically stacked arrays. The arrays were mounted on telescoping towers, and the center of the arrays were 80 ft above the base level. The gain of an array was measured as 12 db above an isotropic radiator in free space, with a horizontal beamwidth of 50°. The gain and beamwidth of the antennas at both ground terminals were measured by a C-131 aircraft equipped with a 50 Mcps dipole antenna and receiver. The height of the antennas was approximately 315 feet above the mean foreground elevation. The actual foreground level varied approximately ± 40 ft.

Figure 27 is a basic block diagram of the ground receiving facility As indicated, the system could be operated in either or both the FSK-4 and FSK-3 configuration. The basic function of the teletype converter was to convert the synchronous 5-bit teletype code into the conventional 7-bit code required by the teletype printer. The converter received information from

the FSK-4 or FSK-3 system or from a separate receiver used for monitoring ground-to-air transmissions originating from the Prospect Hill site. (This last receiver was essentially the same as that used in the airborne terminal.) The error counters were used for determining baud error rates in the air-to-ground transmissions; this measurement required a continuous transmission of alternate marks and spaces from the airborne terminal. The general purpose receiver shown was coupled to a directional, rotatable antenna, and was used primarily for noise and interference measurements. The remote control equipment permitted unattended operation of the receiving site from the ground transmitting site at Prospect Hill.

FSK-3 and FSK-4 Receiver Systems

Since the FSK-3 dual space diversity receiving system manufactured by the National Company closely approximated the specifications set for the ground receivers, three of these equipments were procured to provide the six-space diversity feature required at the ground site. The National Company contract also required development of the necessary additional equipment to provide the FSK-3 with a baud-synchronous matched-filter detection capability. This procedure permitted early air-to-ground tests using the FSK-3 while the additional equipment was under development, and later permitted simultaneous error-rate comparisons between narrowband filtering with envelope detection (FSK-3) and baud synchronous matched-filter detection (FSK-4).

A detailed description of the FSK-3 receiver may be found in the manual "Instructions for Operation and Maintenance of Communications Set, National Co., Inc. FSK-3". A simplified block diagram of the receiver is shown in Fig. 28. After passing through the RF amplifier, which provided a maximum gain of 40 db with a noise figure of 4 db, the 49.62 Mcps signal was mixed in the converter IF chassis with the output of the HF local oscillator to provide an IF centered at 2.2 Mcps. At this point the signal was applied to two parallel crystal filters having bandwidths of 1.5 kcps. One filter was centered at the mark frequency (2.2 Mcps plus 3 kcps) and the other at the space frequency (2.2 Mcps minus 3 kcps). The filter outputs were then added and mixed with the output of the LF local oscillator to provide an IF signal centered at 50 kcps. The 50 kcps signal was applied to the recorder-AGC channel. This channel, after detection, supplied a delayed AGC voltage that was in turn applied to the RF amplifier, and an undelayed AGC was applied to a stage in the converter
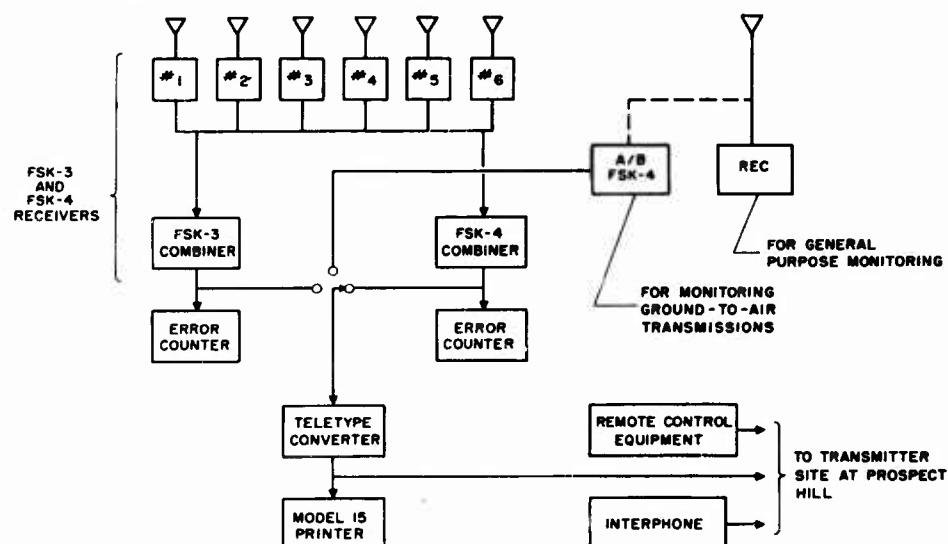
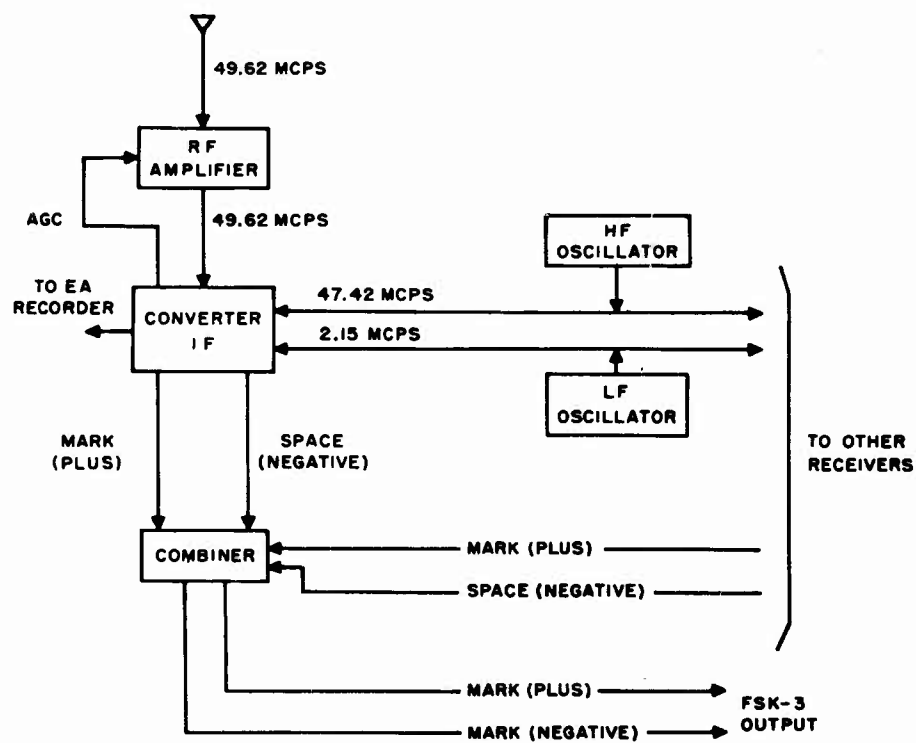Figure 27. Block Diagram of Ground Receiving System

Figure 28. Basic Block Diagram of FSK-3 Receiver

IF. Through a switching arrangement, each receiver could be operated on its own AGC voltage, or all receivers could be slaved to a common AGC. The delayed AGC operated in such a manner that tne RF signal would have had sufficient strength to overcome receiver noise before the AGC began to act in the RF amplifiers. A switch permitted selection of an AGC time constant of either 0.1 or 12 seconds.

The 50 kcps signal was applied to a second channel where, after amplification and limiting, it was passed through two parallel filters, one centered on the mark frequency (53 kcps) and the other on the space frequency (47 kcps). Filter bandwidths could be set at either 800 or 200 cps. Each filter was followed by a diode envelope detector so connected that the detected mark signal was positive and the space signal was negative. Receiver combining was accomplished simply by connecting the outputs of all mark detectors together in the combiner chassis. Thus the receiver with the maximum mark signal would instantaneously bias off the mark detectors of the other receivers. The outputs of the mark and space detectors were then added in a resistance network and passed through a low-pass filter whose cut-off frequency could be varied in steps from 37 to 750 cps. The signal was then applied to a Schmitt trigger circuit which fired when the signal reached a threshold level. The output thus had two discrete levels, one for mark and one for space; phase inversion was employed to provide either a positive or a negative mark output.

Figure 29 is a simplified block diagram of the FSK-4 system as employed at the ground site. The units that were developed and added to the original FSK-3 configuration include the baud-synchronous detector and combiner, the timing acquisition unit, timing generator, frequency synthesizer, AFC unit and a 1 Mcps crystal oscillator. A detailed description of their operation will be found in "Development of FSK-4 Receiver System," final report on Contract AF19(604)-3070.

The baud-synchronous integrators, or matched filters, consisted of a parallel pair of crystal filters for each of the six receivers, one filter centered on the mark frequency (47 kcps in the FSK-4) and the other on the space frequency (53 kcps). The signals applied to the integrators were taken from the recorder channel in the converter IF chassis. Because of the very high Q of the filters, the voltage buildup at a filter output upon application of a signal was nearly linear with time over the duration of one baud (30 milliseconds). At the end of each baud, a one-millisecond pulse was applied to the circuit to dump, or quench, the energy in the integrators quickly. Filter bandwidths of 14, 70 or 500 cps were available through a switch selector.
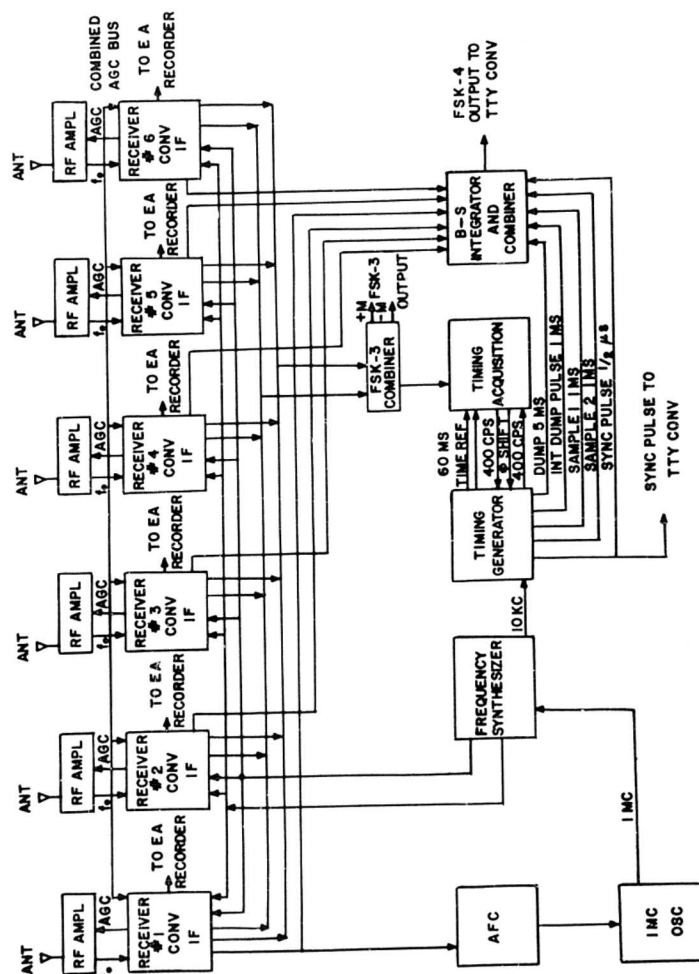
Figure 29. Simplified Block Diagram of Ground Receiver

The outputs of the twelve integrators (six at 47 kcps and six at 53 kcps) were applied to the combiner chassis. Each of the signals was applied to a diode detector that was normally gated on for one millisecond at the end of each baud; provision was made for ungated detector operation. The six 47 kcps diode detectors were connected and the output, after stretching, was stored in a capacitor. A similar system was used for the 53 kcps detectors. The stored space signal was inverted and this signal, together with the stored mark signal, was added in a summing network. The result, after limiting, was then sampled by a 1/2 microsecond pulse. A pulse appeared at the output when a mark was present; a space produced no pulse. This signal, together with the coincident timing pulses, was applied to either the teletype converter or the error detector.

Efficient baud-synchronous detection required accurate synchronization between the receiver timing and the received signal. The timing acquisition unit and the timing generator generated the dumping and sampling pulses required by other circuits in synchronism with the timing of the received signal.

Preceding each air-to-ground transmission, a thirty-second period of alternate mark-space transmission was sent for timing acquisition. The sixty-millisecond square wave appearing in the FSK-3 combiner during the synchronizing period was applied to the timing acquisition unit. A stable locally-generated sixty-millisecond square wave was then compared with this signal in a phase detector. The output error voltage was then applied to a servo system which adjusted the locally generated square wave until it was in proper phase with the received square wave. At the end of the synchronizing period the servo system was locked for the duration of the message; the overall system frequency stability was such that adequate synchronization would be maintained for at least one hour after lock-up. From the phase-corrected sixty-millisecond square wave, the timing generator produced the required sampling and dumping pulses.

Since very narrow pre-detector filter bandwidths were employed, AFC was required to compensate for system frequency changes, caused principally by Doppler shifts up to 40 cps induced by aircraft velocity. The two local oscillators used in the FSK-3 are not used in the FSK-4 but from an AFC-corrected frequency standard operating at 1 Mcps with a long term stability of one part in 10^8. The AFC unit was basically a 53 kcps discriminator with a very steep slope. The 53 kcps signal was derived from the recorder channel of one receiver. This frequency was chosen rather than 47 kcps since it was the one transmitted under quiescent

conditions. The dc output of the discriminator was applied to the 1 Mcps standard to control its output frequency. It may be noted that Doppler shifts cause the same percentage change in the baud frequency (or timing) as in the transmitted radio frequency. Thus an AFC system that controls the receiver frequency standard by means of information derived from the received frequency will maintain the receiver baud rate equal to the transmitted rate. From the output of the 1 Mcps standard, the frequency synthesizer generated the 2.25 Mcps and 47.42 Mcps injection frequencies required by the converter-IF chassis, and a 10 kcps signal required by the timing generator.

Associated Equipment
RECEIVER TIMER

The teletype converter at the ground receiving site required 1/2 microsecond timing and signal pulses. Since the FSK-3 equipment provided only a two-level mark space signal at its output, a timing unit was designed to couple the FSK-3 to the converter. The timer had two functions:

(a) To generate timing pulses of 1/2 microsecond duration spaced 30 milliseconds from a stable 1 kcps input.

(b) To sample the output of FSK-3 combiner with the timing pulses. A 1/2 microsecond pulse was produced if the combiner had a mark output at the sampling time; no pulse was produced for a space. An advance-retard switch was provided for setting the sampling pulse in the center of the output mark or space waveform from the combiner. The stability of the overall system timing was such that once centered, the timing of sampling pulses did not require adjustment for a period of at least one hour.

FSK-3 ERROR DETECTOR

Error rate measurements were made on the basis of a continuous alternate mark-space transmission. In this case, the output of the FSK-3 combiner was a square wave with a period of 60 milliseconds. The square wave is serrated by noise pulses when the signal-to-noise ratio is low. In the error detector, a local, correct "message" was generated simply by triggering a binary stage with the 30 millisecond timing pulses. Errors were detected by sampling the combiner output at the center of each baud. An error pulse was generated if the received message differed from the

local message at the sampling time. The error pulses were then totaled
on an electro-mechanical counter.

FSK-4 ERROR DETECTOR

The FSK-4 error detector was basically the same as the FSK-3. Some
additional circuitry was required to convert the FSK-4 combiner output
pulses to a corresponding square wave for comparison with the locally
generated message.

FIELD STRENGTH RECORDER DRIVER UNIT

The recorder driver unit at the ground facility recorded the signal
strength received on each of the six antennas. The measurement was made
by employing the undetected 47 kcps and 53 kcps mark-space outputs of the
converter IF chassis associated with a particular antenna. This output was
bandlimited to either 200 or 800 cps, depending on the bandwidth switch
setting on the receiver. The 47 kcps and 53 kcps channels of each converter
IF were amplified separately and applied to common-load detectors. Thus
the noise bandwidth of the recorder driver channel was greater than 200
cps, and could be approximated by 400 cps. The detected output served
to drive a one-milliampere full scale recorder, giving an indication of
signal strength present in either of the two filters.

The response of this equipment was limited solely by the recorder and
was of the order of 0.5 seconds for 90 percent of full scale deflection. A
gain control was used in each amplifier for calibration balancing of the
output. Six such units were employed so that the received signal strength of
each of the six antennas could be recorded independently on separate
recorders.

SIGNAL GENERATOR

A calibrated, crystal-controlled signal generator was used at the ground
site for receiver alignment and calibration. The generator was later modified
in the laboratory to provide alternate mark-space capability.

TELETYPE SYSTEM IMPLEMENTATION

A 60-wpm synchronous teletype channel was implemented to study the
feasibility of such a system for airborne use. Although this equipment was

not used in evaluating the performance of the air-to-ground communications circuit, a brief description of a few of its characteristics may be of interest.

It appeared that some advantage in signal-to-noise ratio might be gained by slowing the information rate somewhat and thus narrowing the bandwidth requirements of the receiver. The "start" and "stop" bauds were stripped from each teletype character and the remaining 5 information bauds were re-timed so they would be transmitted as a continuous stream of 30 millisecond bauds. Thus the information could be sent in 150 milliseconds instead of 110 as would have been the case. This also allowed for synchronous operation. To utilize the data at the receiver, the "start" and "stop" bauds must be re-inserted and the bauds re-timed to provide a compatible signal for the receiving teletype machine.

To translate the sequence of received bauds into a corresponding sequence of five-baud teletype characters, a periodic synchronizing stream at 1/5 of the baud rate had to be derived. A 5-fold ambiguity had to be resolved in the starting point of this synchronizing stream relative to the

baud stream. Furthermore, it was felt desirable to do this using only properties of the binary valued digit stream rather than superimposing any additional analog modulation characteristics, and it was required that this synchronization be achieved automatically without manual trial-and-error methods. The solution chosen was to introduce a definite length sequence of bauds at the beginning of each message that could be automatically recognized by digital circuitry at the receiver.

The restrictions on the choice of such a synchronizing pattern were determined by the requirements that:

(a) It should be possible to recognize the pattern even if there are a few digit errors.

(b) It should be extremely unlikely that the pattern recognizer be triggered by random digit sequences arising from either normal message content or noise-produced sequences.

(c) The pattern itself should not tend to cause early triggering when a few erroneous digits are present.

The first two requirements placed restrictions only on the length of the sequence and the number of digit places that must agree in the recognizer. On the basis of these two requirements, almost any sequence of proper length chosen at random would be adequate. However, the third requirement meant that the received pattern should look very unlike the stored pattern until the two line up exactly.

Synchronizing patterns possessing this necessary property were investigated at some length by Barker[8] who established methods of constructing these patterns. While these patterns are not necessarily optimum, they are far better than could be expected if they were chosen at random. A "Barker sequence" of 49 bits was chosen for the synchronizing pattern in the present system.

The teletype system implementation required considerable digital data processing equipment at each end of the circuit to perform the baud-stripping and re-insertion and re-timing at both terminals and also to provide initial synchronization. Equipments were designed and built as "brassboard" models. Approximately 1000 transistors were required for each terminal. The teletype equipment operated successfully on the ground but because of the environmental problems of vibration and temperature variation it did not have sufficient reliability to be used for accurate system evaluation in the air.

System Operation Procedures

Proper operation of the ground receiving equipment during the air-to-ground flight tests required periodic alignment procedures as outlined in the FSK-3 and FSK-4 instruction books. The frequency of these checks varied with the flight test program schedule, but in general they occurred every three or four flights and also whenever equipment performance seemed to indicate a requirement for such tests. In addition to the above more detailed equipment tests, pre-flight receiver balancing procedures were formulated with National Company engineers. These procedures called for adjustment of the receiver gain. AGC-recorder channel gain and separate adjustments of the mark and space channel gains to insure balanced channel gains throughout the entire six diversity receiving system. Upon completion of the receiver balancing procedures, similar balancing procedures were performed on the auxiliary Esterline-Angus driver amplifiers in conjunction with receiver calibration. Receiver calibrations were made just prior to the start of each flight test recording, at the completion of the flight test, and, when possible, spot checks or complete calibrations were made during the course of a flight.

Receivers were calibrated by inserting standard signals into each of the six receivers and recording deflection vs. signal strength for each of the six receivers. The recorder was usually balanced at full scale deflection for a signal on the order of 110 dbm. The signal strength was

then decreased in five-db steps, and the chart level for each step was
recorded from 110 to 140 dbm and for the signal generator off condition
(receiver front end noise). The FSK-3 and FSK-4 combiners were
balanced under a no-input signal condition to obtain equal signal distribu-
tion of marks and spaces at the output of the combiner.

The major portion of the tests were performed with the receiver
parameters as given in Table 2. In cases where the parameter was variable,
the variability available was noted as was the position used during the tests.
Exceptions to these conditions were noted on data sheets.

TABLE 2. TABULATED RECEIVER PARAMETERS

Receiving System Parameter	Variability	Variability Generally Employed
Mark and space information channel bandwidth	200 or 800 cps	200 cps (noise channel bandwidth approximately 400 cps)
AGC Channel Bandwidth	none	Fixed at 3 kcps - Two 1500 cps wide filters centered at mark and space frequencies
AGC Function Selector Switch	Calibrate Separate Master Slave	Separate
AGC Fast-Slow Switch	Fast - 0.1 sec Slow - 12 sec	Fast
FSK-3 Combiner Post Detection Filter Bandwidth	37, 75, 150, 300 500 & 750 cps	37 cps
FSK Baud Synchronous Integrator Bandwidth	gnd - 14, 70, 500 air - 40, 140, 500 cps	gnd - 14 cps air - 40 cps
FSK-4 Combiner Integrator Baud Sampling Switch	On-Off	On

GROUND TRANSMITTING STATION

The ground transmitting station was located at the summit of Prospect Hill, Waltham, Massachusetts. This site was chosen for the height of the hill above the surrounding territory, the fairly smooth foreground and the ease of access from Hanscom Field. This station was equipped to serve as the ground system control center. Major components were as follows: Transmitting antenna array; 50 kw radio frequency amplifier; 20 kw radio frequency amplifier; FSK exciter-driver; teletype digital equipment (not used for system evaluation); operating position and remote control center.

Transmitting Antenna Array

The antenna consisted of a center fed array of eight full-wave horizontal elements in front of a reflecting screen. The entire array was 22 ft wide by 80 ft high and was mounted on a 110-ft tower and tilted 5°. The antenna bearing was 2° east of true north.

The antenna was designed to operate at a frequency of from 49.2 Mcps to 49.9 Mcps with a VSWR of 1.1:1. In the operating band of 49.62 Mcps ± .1 Mcps the design VSWR was 1.06:1. The horizontal beamwidth was measured as about 45° between half power points and the vertical beamwidth was designed to be 14.5°. The vertical side lobe suppression was better than 20 db while the back lobe was estimated at 25 db down. The peak power rating was 200 kw cw. The gain of the array was measured as 17 db above an isotropic radiator with the peak power directed at an angle of 5° above the horizon.

Final RF Amplifier
FIFTY KILOWATT RF AMPLIFIER

The output stage of the ground transmitter consisted of the 50 VHF amplifier group, part of Radio Transmitting Set AN/FRT-34. This equipment consisted of a class B grounded grid linear amplifier stage with associated control equipment rectifier unit and cooling system.

A water load capable of dissipating the full output of this stage provided calorimetric measurements of power output for calibration purposes.

Further information concerning this equipment is available in the "Instruction Book for 50 VHF Amplifier Group", Contract No. DA-36-039 SC-64440, dated 15 November 1959.

TWENTY KILOWATT RF AMPLIFIER

A Collins 205G-1 linear amplifier was used to drive the final RF amplifier stage. The 205G is in itself a complete transmitter with integral high voltage supply and associated air cooling equipment. Considerable effort was devoted to interconnecting the control and interlock circuits of the two amplifier to achieve operation as a unit. The 205G was capable of developing full output with an input signal of 0.5 watt. The necessary driving power was generated in the FSK exciter equipment. Further information concerning this equipment is available in the "Instruction Books for 205G-1 Transmitter", 520-5361-00, Collins Radio Company, Cedar Rapids, Iowa.

Exciter

The function of the ground station exciter was to generate stepped-frequency mark and space signals at the transmitted frequency accurate to about one part in 10^7 and at a level suitable for driving the 20 kw transmitter. A frequency-time diagram of the modulating signal is shown in Fig. 30.

A basic block diagram of the exciter is shown in Fig. 31. From a stable 100 kcps frequency standard, the timer generated the required synchronizing and gating pulses. The frequency synthesizer generated three frequencies sequentially gated into a common output by a series of 10 millisecond pulses from the timer. From this common output one of two frequencies, similarly generated, was subtracted resulting in either a mark or a space sequence, the choice being determined by the synchronized message input. The output of the frequency synthesizer was then multiplied and amplified and after filtering was applied to the 20 kw transmitter. Conventional vacuum tube techniques were used throughout with no attempt to miniaturize the equipment.

TIMER

A simplified block diagram of the timer is shown in Fig. 32. Input signals from a 100 kcps frequency standard (General Radio Model 1100-A) were applied to a decade divider. The resulting 10 kcps waveform was then divided by six to provide pulses at the 1.666 kcps rate required by the frequency synthesizer. A 1 kcps pulse train, also required by the synthesizer, was obtained from a second decade divider. The 1 kcps signal was further divided by 10 and applied to a chain of three binary stages, which, with
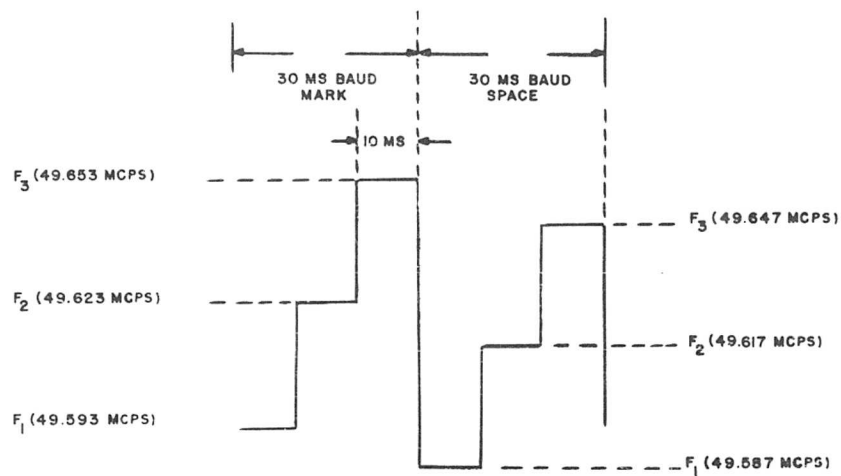
44

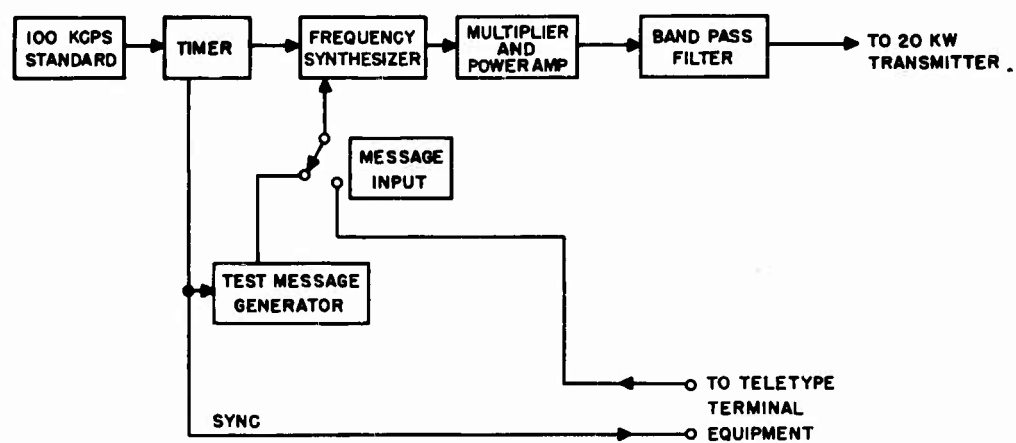Figure 30. Frequency-Time Diagram of Ground Exciter

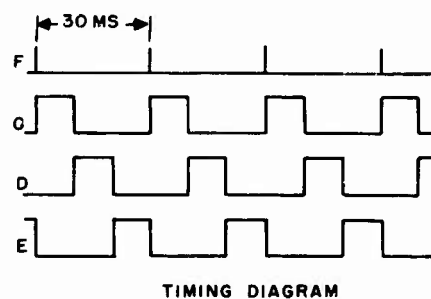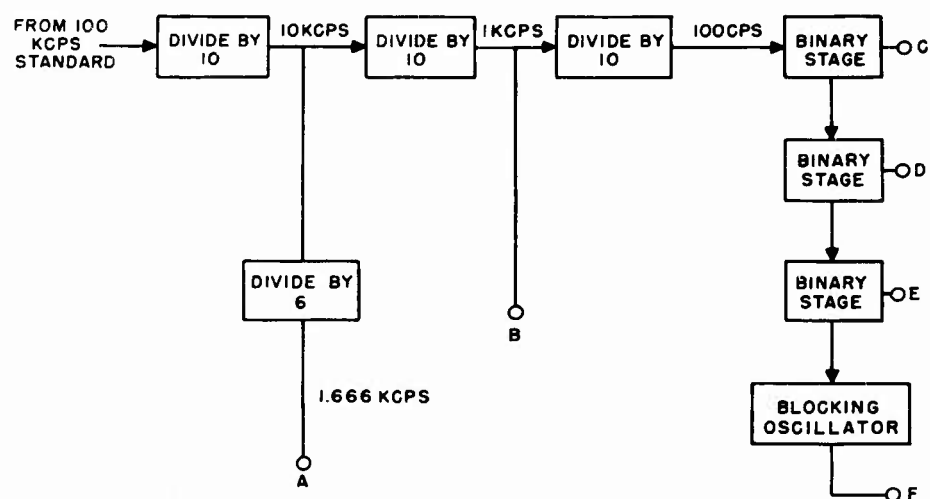Figure 31. Block Diagram of Ground Exciter

Figure 32. Block Diagram of Ground Timer and Timing Diagram

appropriate feedback, provided the waveforms indicated in Fig. 32. A blocking oscillator followed the third binary stage to provide 1/2 microsecond synchronizing pulses spaced 30 milliseconds. Waveforms C, D, and E were required in the synthesizer to gate the three frequencies sequentially.

FREQUENCY SYNTHESIZER

A basic block diagram of the frequency synthesizer is shown in Fig. 33. The frequency synthesizer generated six stable frequencies using the outputs of the timing unit.

A synchronously pulsed oscillator was tuned to a desired frequency and pulsed on and off so that succeeding pulsed oscillator signal groups were identical in terms of oscillator frequency and waveform. The pulses were phase coherent in the sense that the phase of the oscillator signal was exactly the same at the start of each pulse. The waveform of the pulsed oscillator produced line spectra enveloped by a (sin x) function. These spectral lines were located at frequencies n/R (R being the pulse repetition period), and spaced at intervals equal to the repetition frequency (f_r) of the pulsing wave. These lines did not usually include the oscillator frequency unless it happened to be an exact multiple of $1/R$. The spacing between zero points on the envelope was determined by the pulse duration.

The tuning of the synchronously pulsed oscillator or slight drift therein does not result in a shift in the frequency of these lines but rather shifts the distribution of energy content according to the familiar $(\sin x/x)^2$ spectrum of the pulse waveform. Thus the pulsed oscillator concentrated the energy output in the region of the desired spectral lines, and the frequency stability of the lines was dependent only on the stability of the gating pulses. The frequency of the gating pulses was derived from a very stable standard.

Selection of the desired spectral line was made with the use of a narrow bandpass crystal filter, two mixers and a crystal controlled oscillator. The output spectrum of the pulsed oscillator was converted to a frequency band so that the desired spectral line fell within the bandpass of the crystal filter. After selective filtering of the desired spectral line at the filter frequency, the desired spectral line was then converted back to the desired frequency by remixing with the crystal oscillator frequency. Thus the desired spectral line was selected independently of drift in either the pulsed oscillator free-running frequency or the frequency of the crystal controlled oscillator.
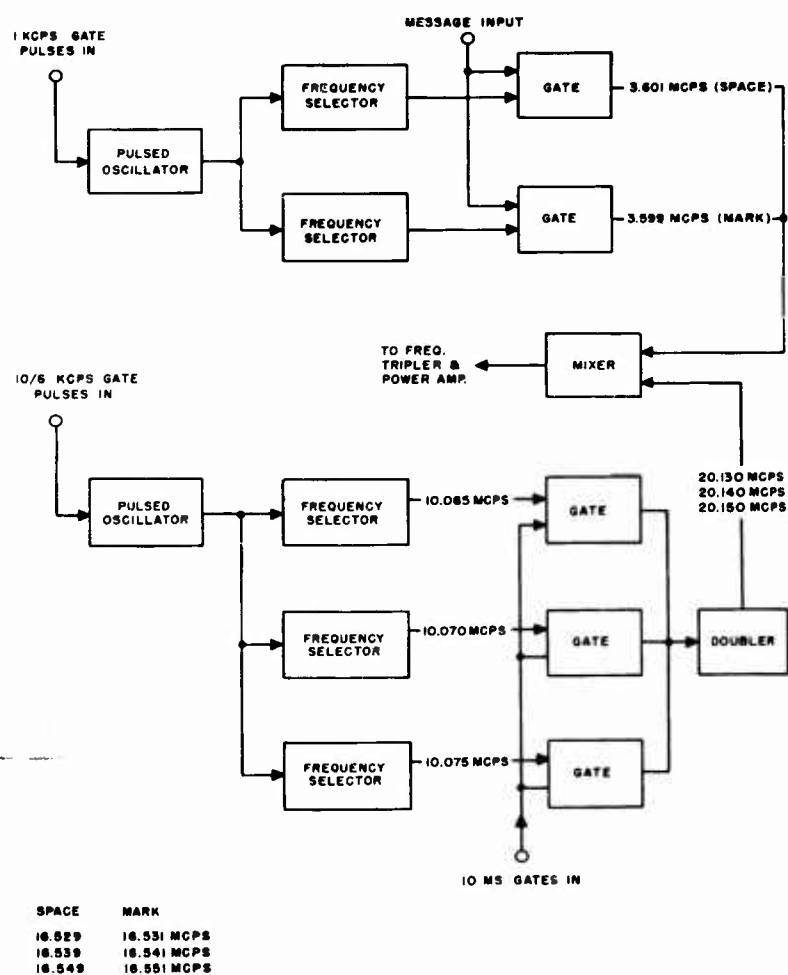
Figure 33. Block Diagram of Ground Frequency Synthesizer

SPACE	MARK
16.529	16.531 MCPS
16.539	16.541 MCPS
16.549	16.551 MCPS

The spectrum generator of the synthesizer used to produce the desired output frequencies of the system employed three drift-canceled spectral line selectors operating from a single synchronously pulsed oscillator to yield the final transmitter output frequency jumps spaced 30 kcps apart. The synthesizer also had two additional spectral line selectors operating from a second synchronously pulsed oscillator to yield the (plus and minus 3 kcps) frequency shift keying of the stepped output frequencies.

The frequency of the first pulsed oscillator was set to 10.070 Mcps and was synchronously pulsed with 10/6 kcps gate pulses. The pulsed oscillator yielded spectral lines at $(n)(10/6)$ kcps with the energy concentrated in the region of n equal to 6042. The three spectral line selectors served to pick out harmonics of the input pulse at n equal to 6039, 6042 and 6045 yielding the frequencies 10.065, 10.070 and 10.075 Mcps. These frequencies were then doubled to produce 20.130, 20.140 and 20.150 Mcps and then gated in time sequence of 10 ms duration. These stepped output frequencies were then fed to a common mixer (see Fig. 33).

The other input to this common mixer was derived in a similar manner from a synchronously pulsed oscillator operating at a free running frequency of 3.600 Mcps and gated by a 1 kcps pulse derived from the timing unit. Two spectral lines were selected to yield output frequencies of 3.599 and 3.601 Mcps. These mark and space injection frequencies were gated in a time sequence of 30 ms controlled by the message input and were fed to the common main mixer where they were subtracted from the doubled step frequencies of 10 ms duration as described above. This yielded a total of six frequencies; 16.531, 16.541 and 16.551 Mcps representing a mark or 16.529, 16.539 and 16.549 Mcps for a space. These steps, representing either a mark or a space, were then tripled and power amplified in the exciter section to yield the desired final transmitting frequencies centered around 49.620 Mcps at a power level of 8 watts. Due to keying transients, this signal occupied an undesirably wide spectrum which was reduced by passing it through a bandpass filter before applying it to the 20 kw transmitter. The filter was composed of coupled coaxial resonators and had a 3 db bandwidth of 130 kcps.

Associated Equipment
OPERATING POSITION

Remote controls were provided for the operation of all major components of the ground system, including telephone dial control of equipment at the receiving site and land-line teletype facilities to enable a single operator

to carry out two way teletype communications with the aircraft. The operating position also included HF and UHF communications equipment to furnish voice communications with the aircraft in support of the test program. This equipment included: Collins KWS-1 HF transmitter; Hallicrafters BC 610 HF transmitter; Collins 75A-4 HF receiver; T-217A/GR UHF transmitter; and R-278B/GR UHF receiver.

OPERATING PROCEDURES

The transmitted signal was monitored carefully at all times to eliminate any possible errors. The power output was observed at the input to the antenna and again at the remote operator's position. A power output monitor was arranged to sound an audible alarm in the event of any decrease in power output under a preset level. During most of the transmissions a continuous recording of transmitter output power was made.

In the tests where an unmodulated carrier was transmitted, the frequency was monitored by means of a Hewlett Packard 524B electronic counter. Whenever the carrier was being modulated by the FSK exciter, a dual beam oscilloscope was used to examine several waveforms within the exciter. The waveforms showing the mark-space gating and the overall gating of the six frequencies were continuously monitored. Automatic switching was used to key the signal on and off for identification and to allow for noise measurements.

AIRBORNE TERMINAL
Airborne Antennas

The aircraft 50 Mcps antenna system was designed and installed by the Boeing Airplane Company under contract to AFCRL. The system consisted of wingtip antennas, a nose antenna and a tail antenna. The nose and tail antennas transmitted at high power while the antennas on each wingtip were intended to provide a dual space diversity receiving system.

The wingtip antenna consisted of a horizontal, three-element parasitic array (Fig. 34). The arrays on either wingtip were mirror images and had a single driven element on each side of which there was a parasitic element. The two parasitic elements, when remotely switched to act as either directors or reflectors, produced a reversible forward or aft unidirectional pattern with a measured gain of about 6 db over an isotropic radiator.

The nose antenna installation consisted of a loop mounted within the nose radome surface. This loop was loaded electrically to a full wavelength and fed in the correct mode to obtain broadside directivity. Mounting the loop approximately 0.70 wavelengths ahead of the nose radome bulkhead produced a unidirectional pattern and the forward gain was increased. The measured gain of this installation was 7 db over an isotropic radiator. The beamwidth was measured as approximately 60° between half power points.

The aft antenna installation consisted of four elements, two on each side of the vertical tail fin of the aircraft (Fig. 35). The elements on each side were spaced 63 wavelengths vertically and were fed in phase; however, they were fed 180° out of phase with the two elements on the opposite side of the fin. Feeding was accomplished through a suitable power dividing network. Each of the elements consisted of a short folded stub, end loaded with a variable capacitor. Each element produced a cardioid pattern. The patterns of the opposed elements added to produce an omnidirectional pattern. The patterns of the vertically stacked element pairs added, thus producing an essentially omnidirectional horizontal pattern with sufficient vertical directivity for a calculated gain of 8.2 db over an isotropic radiator. The measured gain was 7 db at the horizon, while the measured beamwidth was 45°. The gain and beamwidths of all antennas are approximate figures because of the difficulty of performing airborne antenna measurements.

The VSWR of all antennas was less than 1.3:1 over 0.1 Mcps bandwidth. Teflon cabling was used throughout to minimize losses.

Airborne Transmitters

A high-power, class C, RF amplifier was necessary to furnish the required output power for the air-to-ground scatter circuit. Three different amplifiers were employed during the course of this experiment: A 10-kw liquid cooled amplifier; a 5-kw evaporative cooled amplifier; and a 5-kw air cooled amplifier.

TEN KW LIQUID COOLED AMPLIFIER

The major portion of the air-to-ground data was obtained using this transmitter operating at an output power of 5 kw. The equipment was designed by Continental Electronic Co. and it was cooled by conventional liquid techniques. The heat generated in the final amplifier tube was transferred to a liquid-to-air heat exchanger by circulating a liquid coolant medium through the system.
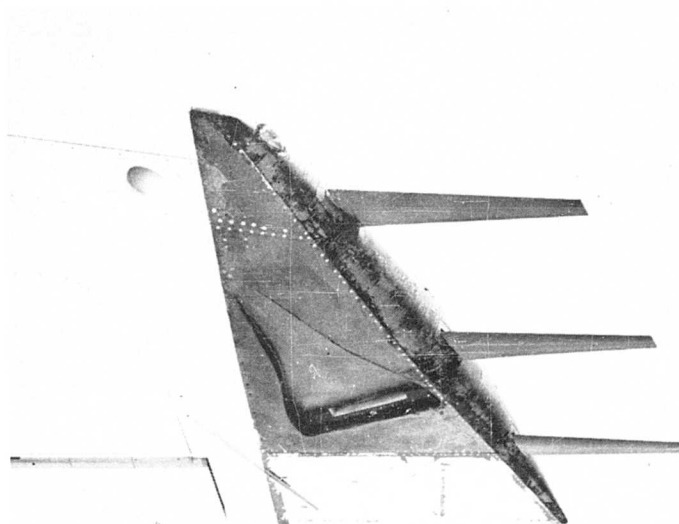
Figure 34. Wing Tip Antenna On KC-135

Figure 35. Tail Antennas On KC-135

The amplifier circuitry was enclosed in a pressurized cabinet to permit operation at an altitude of 50,000 ft. The heat exchanger components were mounted in a separate enclosure and were designed to permit operation from -65° F to 122° F. Standard tubes were used with the exception that the final amplifier tube liquid connectors were modified to shorten the overall length of the tube. Additional specifications of this unit are as follows:

Power output: 10-kw into a 50 ohm lead;

Excitation: 0.5 watt;

Bandwidth: 350 kcps;

Duty cycle: continuous;

Size and weight

    Amplifier: 4 cu ft, 350 lbs;

    Heat exchanger: 8 cu ft, 150 lbs;

Tubes: 2E26, 4-125A, 4CW10000A (modified).

Further information concerning this equipment may be found in the final report of AFCRC Contract AF19 (604)-3060.

FIVE KW EVAPORATIVE COOLED AMPLIFIER

Substantial reductions in overall weight and size were achieved in this amplifier (designed by the Martin Co.) by eliminating the conventional heat exchanger components. Heat generated in the amplifier tubes was conducted into a water filled reservoir, causing the water to boil. The boiling water served as a coolant because of vaporization and the release of steam. The difficulties encountered in removing heat from other parts of the circuitry caused operation of this developmental model at a reduced duty cycle. A photograph of this amplifier is shown in Fig. 36.

Specifications are as follows:

Power output: 5 kw into a 50 ohm lead;

Excitation: 5 watts;

Bandwidth: ± 100 kcps;

Duty cycle: 2 min on, 4 min off (or 15 min on, 45 min off);

Operating temperature: 10° F to 110° F;

Operating altitude: to 10,000 ft;

Size and weight: 3 cu ft, 185 lbs;

Tubes: 4CX300A (modified), 3W5000A (modified).

Further information concerning this equipment may be found in the final report of AFCRL contract AF19(604)-3863.
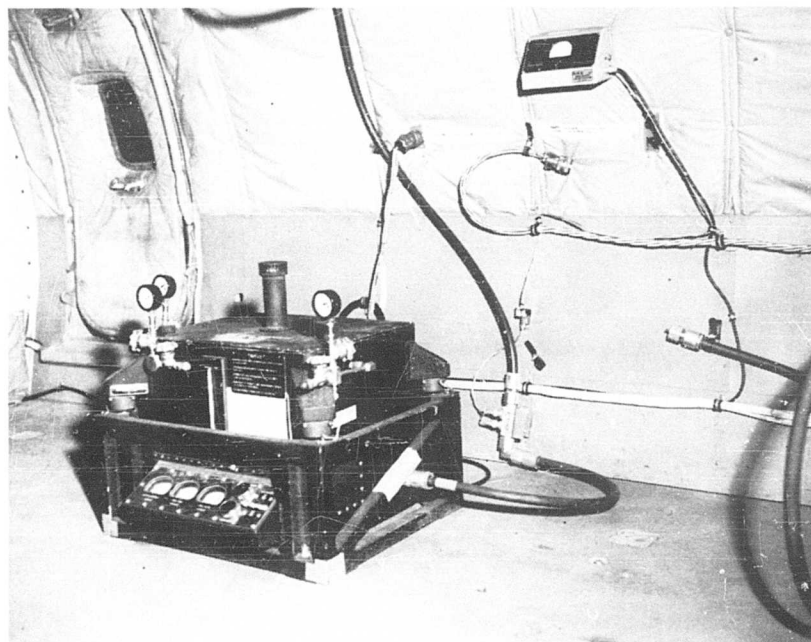
Figure 36. Airborne 5 KW Evaporative Cooled Transmitter

FIVE KW AIR COOLED AMPLIFIER

This laboratory constructed equipment was intended to serve as an interim
model to allow initial tests of other parts of the system. Design specifications
were relaxed wherever feasible to reduce development time and to expedite
construction of this unit. Standard off the shelf components were employed
throughout. Size and weight were of secondary importance. Air cooling of
the final amplifier tubes, although relatively inefficient at high altitudes,
was employed in order to avoid the complexities of liquid coolant systems.

Airborne Exciter

The function of the airborne exciter was to generate mark and space signals
at the transmitter frequency, accurate to about one part in 10^7, and at a
level suitable for driving one of the three airborne transmitters. The
mark frequency was 49.623 Mcps and the space frequency 49.617 Mcps.
The baud duration was 30 milliseconds (33 1/3 bauds per second). While
similar to the ground station exciter in many respects, the airborne
equipment was considerably simpler, since only two output frequencies
were generated.

A basic block diagram of the airborne exciter is shown in Fig. 37.
From a stable 100 kcps standard, the timer generated the required gating
and synchronizing pulses. With a pulsed oscillator technique, two
frequencies of the required accuracy were generated, one representing
a mark and the other a space. A third frequency, similarly generated,
was then mixed with one of the two frequencies; the choice was determined
by the message input signal. The result was then multiplied and amplified
to the level required by the FM transmitter. The sequence of marks and
spaces was determined by the output of either the teletype terminal
equipment or the test message generator. The latter permitted transmis-
sion of continuous marks, continuous spaces or alternates. Conventional
vacuum tube techniques were used throughout and no particular effort was
made to miniaturize the equipment.

TIMER

The timer generated pulses at a precise 1 kcps and 1.666 kcps rate required
by the pulsed oscillators in the frequency synthesizer, and 1/2 microsecond
synchronizing pulses spaced 30 milliseconds apart. The signal from a
100 kcps frequency standard was first divided by 10; the resulting 10 kcps

signal was then divided by 6 to produce the 1.666 kcps pulses. The 10 kcps signal was also divided by 10 to produce the 1 kcps pulses. This frequency was then divided by 30 and triggered a blocking oscillator which supplied the system synchronizing pulses. The airborne frequency standard was a Borg model 1506A with a stability of one part in 10^9 per six-hour period.

FREQUENCY SYNTHESIZER

The airborne frequency synthesizer was identical to the ground station synthesizer with the exception that the airborne unit did not have to generate three step frequencies and therefore the 10.065 and 10.075 Mcps frequency selector channels and the corresponding gates were eliminated. (See Figs. 33 and 38.)

Receiving System

The important parameters of the airborne receiving system are listed in Table 2. The three sequentially transmitted frequencies indicated in Fig. 39 provided triple frequency time diversity, which, when combined with the space diversity feature resulted in an overall six diversity system. The airborne system was almost identical to the FSK-4 equipment at the ground facility. The major differences were that it accepted a stepped-frequency signal and that only one receiver was employed.

A simplified block diagram of the airborne receiver system is shown in Fig. 40. A detailed description may be found in, "Development of FSK-4 Receiver System," final report on contract AF19(604)-3070.

The operation of the RF amplifier and converter IF was the same as described for the ground receiver site. The signal applied to the first mixer differed however in that it was stepped in frequency synchronously with the received signal providing a single frequency at the mixer output. The operation is shown diagrammatically in Fig. 39.

The stepped first mixer injection frequency was generated by the frequency synthesizer using a pulsed oscillator technique similar to that employed in the ground exciter. In this case, the repetition rate of the pulsed oscillator was derived from an AFC controlled 1 Mcps oscillator, thus compensating for variations in the received frequency. The second mixer injection frequency was obtained directly from the 1 Mcps oscillator by multiplying its output by a factor of 2.25.
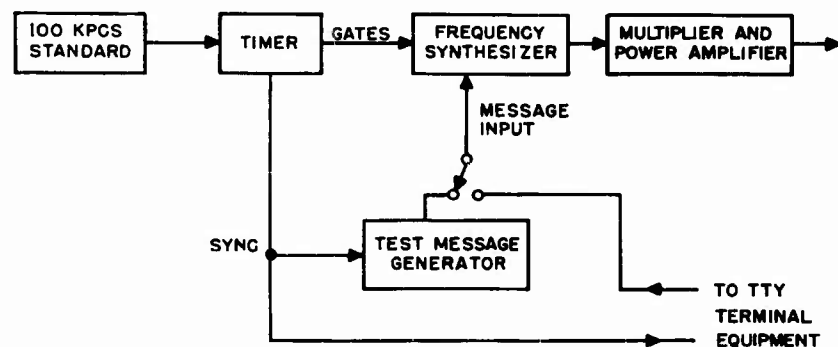
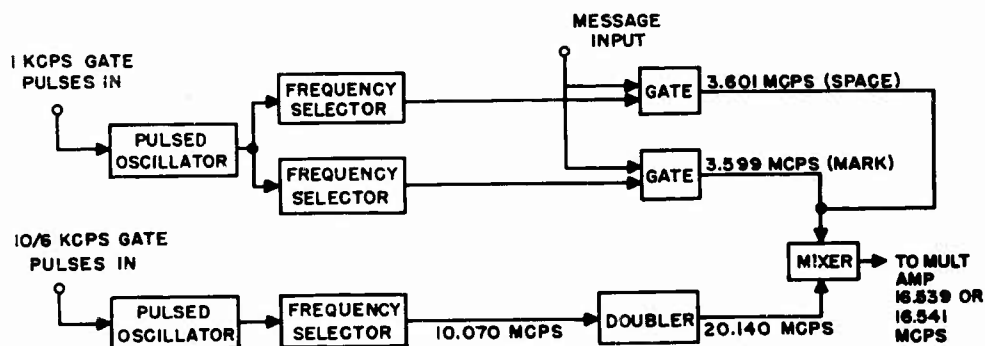Figure 37. Basic Block Diagram of Airborne Exciter

Figure 38. Basic Block Diagram of Airborne Frequency Synthesizer

As indicated in Fig. 39, accurate synchronization had to be maintained between the timing of the received signal and the stepped-frequency injection signal. This was achieved by the timing acquisition unit and the timing generator; the process was somewhat involved, and the details are beyond the scope of this report. As in the case of the ground receiver, timing was acquired in a 30-second period of alternate mark and space bauds preceding each message transmission.

The 47 kcps and 53 kcps signals which were applied to the mark and space integrators, or matched filters, were obtained from the recorder channel in the converter-IF chassis. As indicated in Fig. 39, a received mark or space signal was comprised of three sequentially transmitted frequencies. While the mixing process converted this to one frequency, phase discontinuities occurred every 10 milliseconds. Thus the signal integrators had to be quenched at the end of every 10 millisecond sub-baud period rather than at the end of each 30 millisecond baud period as was done in the ground receiver. The ground and airborne baud synchronous combiners were physically identical; the detectors in the latter case, however, were gated on at the end of each 10 millisecond sub-baud period. The combining and the mark/space decision circuitry that follows was the same as in the ground receiver.

AIRBORNE ERROR DETECTOR

This unit was identical with that in the ground receiver site.

AIRBORNE RECORDER DRIVE UNIT

The airborne recorder drive unit was identical to the ground recorder drive unit. The measurement in this case differed from that at the ground site, however, in that the frequency diversity used and the receiver design resulted in time sequential sampling of the three 30 kcps stepped frequencies. The resulting detected output drove the recorder.

Airborne Terminal Operating Procedures

The operation of the airborne terminal did not differ greatly from that of the ground field site. When the aircraft was to be used as the receiving terminal, the ground transmitter was turned on before takeoff and the receiver tuned and completely checked. After takeoff and while the aircraft was still in line-of-sight of the transmitter, the equipment was given a final check using
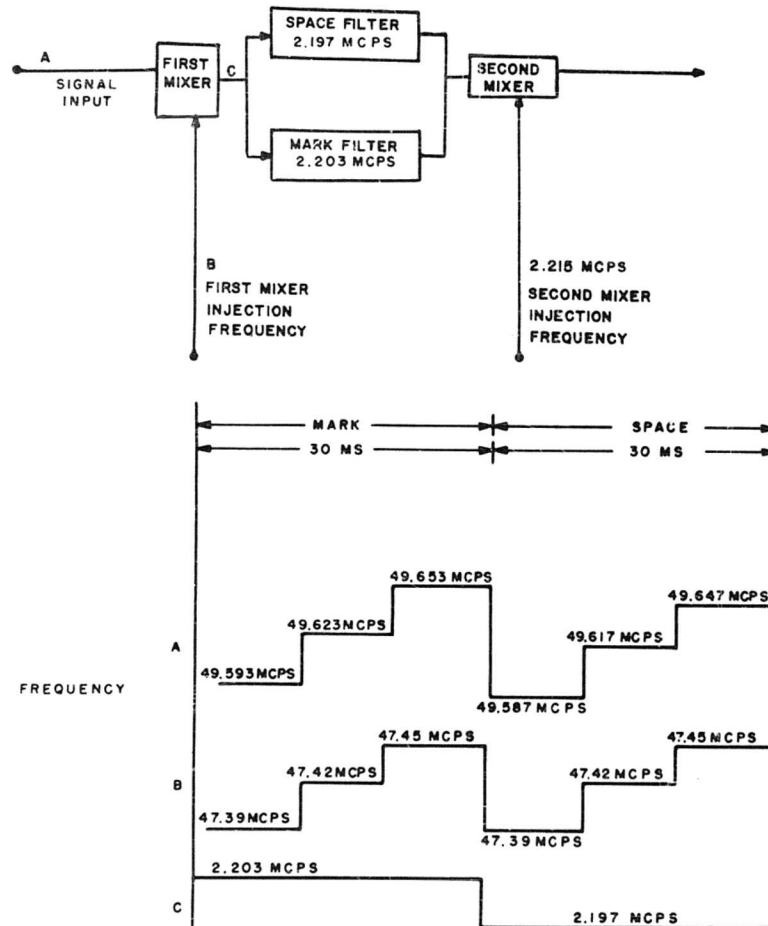
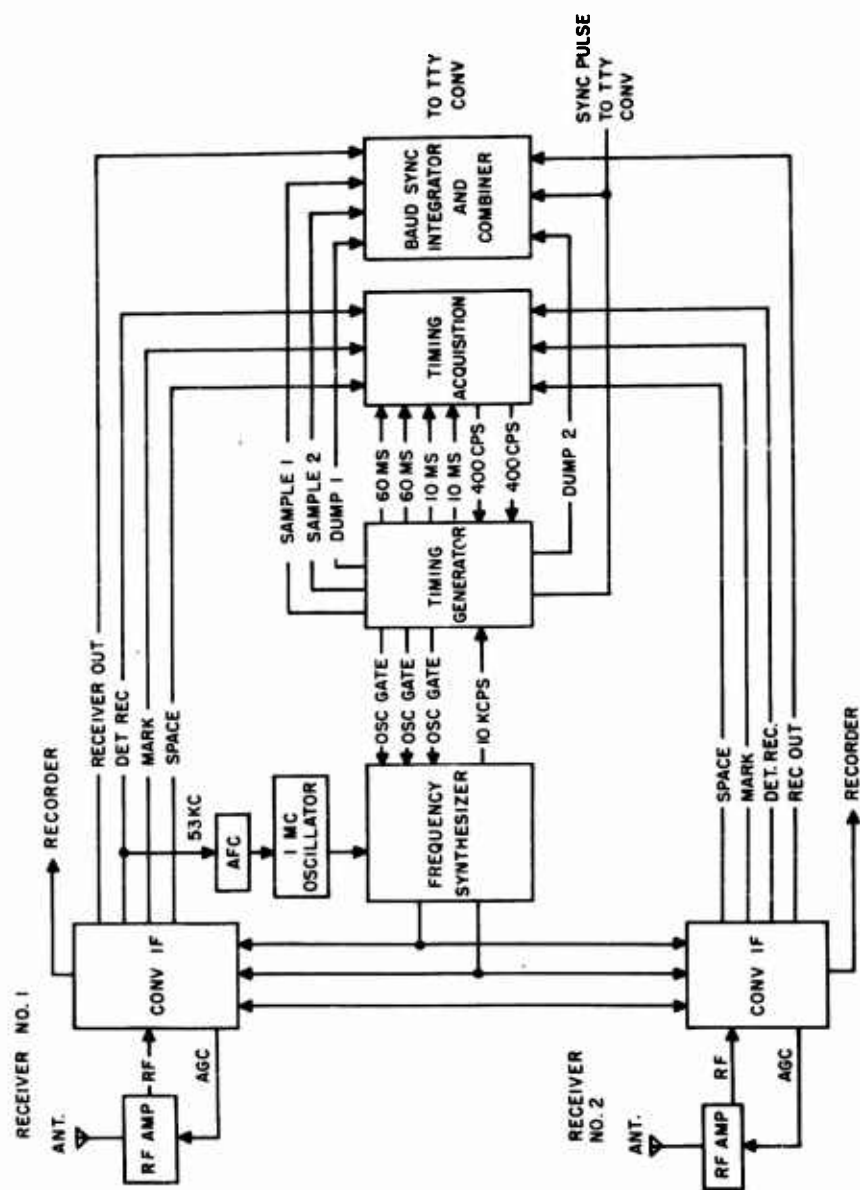Figure 39. Stepped Frequency Mixing of Airborne Receiver

Figure 40. Block Diagram of Airborne Receiver

the strong signals present. At a point when the incoming signal dropped to a level 25 db above the noise, the receiver was calibrated using the local signal generator. Calibrations were repeated every hour to guard against errors involving receiver and recorder amplifier drift. Postponing calibration until the aircraft was out of the strong line-of-sight signal of the transmitter ensured that all recorded signal was entering via the RF amplifier and not leaking into the later stages directly from the interior of the aircraft.

The receiver was monitored continuously during the flight to ensure maintenance of baud and frequency hop synchronization between transmitter and receiver. The signal quality as observed on the recorder was monitored and any unusual characteristics noted by the operators. Baud error counts were obtained in alternate ten second intervals using the Hewlett Packard frequency counter as the readout device. The error data was correlated with signal strength and distance.

The equipment was operated on the ground before takeoff to check both the exciter transmitter and the receiving equipment at the ground station. After takeoff the low power (6 watts) exciter was used as a transmitter in the line-of-sight region to allow for further checking of the receiver without the limitation of final amplifier duty cycle. When the high power was applied to the antenna and throughout the remainder of the flight, the VSWR of the antenna was monitored so that antenna malfunctions of potential danger to the aircraft could be detected. Early in the project, corona and arc-overs had been experienced. The exciter equipment was monitored continuously to ensure that the transmitted signal was on frequency and that the alternate mark-space generator was errorless.

In both receiving and transmitting cases, personnel in the aircraft kept a careful navigation record. By use of the ground-position-indicator (GPI) operating in conjunction with the Doppler navigation system (APN-82), time vs position information was compiled and later used to correlate the signal strength and error data with the distance from the ground site. A record was also kept of flight conditions and observations such as auroral displays which could be useful in interpreting the data.

Appendix B
Airborne Problem Areas

A. S. Orange

WING ANTENNA NOISE

The biggest problem encountered at the airborne terminal was that of the static discharge noise present on the wingtip antennas. A complete experimental examination of the noise was made. On the ground, with the engines idling, no increase in noise was noted above the expected cosmic background noise level present with the engines off. With the engines at full power for takeoff and during the takeoff roll the noise level increased from 5 to 15 db (noise bandwidth: 400 cps). When the plane left the ground the noise level immediately increased to 40 to 60 db above the normal background. This level persisted from takeoff until the tropopause (30,000 to 38,000 ft, depending on meteorological conditions). At the tropopause the noise level dropped off sharply to 10 to 15 db above background noise. Below the tropopause a 40 to 50 db decrease in noise level occurred when the engines were idled. Above the tropopause no change was noted when the engines were slowed to the lowest permissible power setting for the high altitudes. The altitude of the tropopause was determined by the Hanscom Field meteorology center; the figure was checked with the observed altitude of cloud and haze layers. Results are summarized in Table 3.

Various methods were attempted to eliminate static: smoothing the antennas with tape, installing static discharge wicks and pre-RF amplifier filtering. Although some methods were effective below the tropopause, none succeeded in bringing the noise level lower than 8 to 10 db above the normal background over the operational altitude range of the aircraft. The level of noise lowered the received signal-to-noise ratio enough to render these antennas useless. Fortunately, above the tropopause the nose and tail antennas were free from aircraft noise contamination and were satisfactory for receiving purposes. Below the tropopause the noise level on the nose and tail antennas was consistently 35 to 40 db below that on the wings, leading to the speculation that these antennas may have been weakly coupled to the radiation field produced by the discharge from the wingtip antennas.

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TABLE 3
SUMMARY OF WINGTIP NOISE DATA

Condition	Noise Level (400 Cps Bandwidth)
On Ground - Engines Off - Wing Antenna	137 dbm
On Ground - Engines Off - Tail Antenna	137 dbm
On Ground - Engines Idling - Wing Antenna	137 dbm
On Ground - Engines Full Power - Wing Antenna	127 dbm
Immediately After Take Off - Engines Full Power - Wing Antenna	87 dbm
Cruise Power at 20 K' - Wing Antenna	92 dbm
Idle Engines at 20 K' - Wing Antenna	132 dbm
Cruise Power at 20 K' - Tail Antenna	127 dbm
Cruise Power at 30 K' - Wing Antenna	97 dbm
Cruise Power at 40 K' - Wing Antenna	127 dbm
Cruise Power at 40 K' - Tail Antenna	138 dbm
Cruise Power at 30 K' - Wing Antenna Taped	128 dbm
Cruise Power at 40 K' - Wing Antenna Taped	128 dbm

Note: These values are representative of those found over the course of many flights. Noise levels varied considerably from day to day.

HIGH ALTITUDE ANTENNA PROBLEMS

When the tail antenna was first used for checking the airborne transmitters it was observed that although the VSWR of the antenna was 1.2:1 on the ground, at cruise altitude (35,000 ft) the VSWR rose over 1.8:1. This value of VSWR would have prevented the use of the high power final amplifier at altitude. It was found, when the antenna was examined with an impedance bridge, that the resonance of the tail antenna system changed from a frequency 49.62 Mcps on the ground to about 49.9 Mcps at altitude. It was then postulated that the extreme change in temperature encountered on climbing to altitude resulted in detuning of the very critical vacuum capacitors used in end-loading the antenna elements. (See Appendix A.) The antenna system was then retuned to a resonant frequency of 49.4 Mcps in the hope that the resonance would shift to the operating frequency at altitude. This did occur, and the aft antenna system was successfully used at average power levels to 5 kilowatts.

Other airborne antenna difficulties involved high power arc-over and insulator breakdown caused by a combination of close clearances and the effect of high altitude rarified air. The arc-over problem was partially overcome by the application of anti-corona dope and Teflon sheet to the metal aircraft structure adjacent to the antenna elements. Insulation breakdown problems were solved by the use of Fiberglas laminates of high dielectric strength manufactured under conditions of stringent quality control.

Appendix C
Receiver Site 50 MCPS Noise and Interference

L. A. Ames

The minimum galactic noise at the ground receiver site was estimated to be 193 dbw per cycle of bandwidth[9]. Because of the rather remote location of the site from the metropolitan area, little if any noise contribution was expected from man-made sources. During the site survey, a high tension power line was discovered crossing the path of the beam at nearly a right angle. Since the line was of modern construction, little difficulty was expected. Although it would be desirable to eliminate all possible sources of man-made noise when a receiving site is selected, the present site seemed acceptable and had the advantage of the necessary elevation and proximity to the laboratory to lower installation and operating costs. In as much as no suitable noise measuring equipment was available, the field site was activated on the basis of these estimates.

Preliminary tests of background level were attempted after the receivers had been installed. It was immediately obvious that there was not a clear channel, as had been assumed.

Because the narrow band characteristic of the receivers prevented the detection of any intelligence from voice interference, the source could not be determined. Automatic monitoring with a tape recorder connected to the output of an AM-FM communications receiver while scanning the rotatable test antenna finally pin-pointed the direction and provided the call letters of the offending commercial stations. These stations were legally licensed to operate on or near to our exact frequency. It was first believed that an insurmountable problem had been encountered as calculations indicated that, under certain conditions, a signal of 120 dbw might be expected in our 400 cps bandwidth. Because the interference level varied between 117 dbw and 139 dbw with only partial correlation with known interfering transmissions, other sources of noise were suspected. Detailed examinations of the simultaneously recorded output of both the FSK-3 and communication receivers showed a signal (noise) which varied between 128 dbw and 139 dbw.

A portable, low-noise figure, narrow band 50 Mcps receiver and recorder was mounted in a light truck. This, coupled with a motor generator set and portable six-element Yagi on a 20-ft mast, provided the test equipment. Two

parallel 50 kw power lines, vintage 1926, were discovered with this mobile equipment. The two lines ran through wooded areas and so escaped detection at the start. The responsible power company was contacted to arrange tests, and they were most cooperative   Polar plots of the noise were made showing the maximum noise intensity at about 10° each of north at a level of 128 dbw. When one line was deenergized, the noise level dropped to 131 dbw. With both lines out the noise level dropped to 139 dbw, the value of the expected galactic noise. Study revealed that the power line noise occurred only during dry weather; light precipitation or dew was sufficient to reduce the level below detectability at our site (nearly four miles from the nearest approach of the power line). The course of the line extended mainly north for an additional 12 miles before deviating out of the antenna pattern.

Because of the dependence of line noise on local meteorological conditions, its behavior was predictable. Flights could thus be scheduled when the noise level was expected to be low. This proved highly successful.

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APPENDIX C

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AN EXPERIMENTAL AIRBORNE 50 MCPS IONO-SPHERIC SCATTER COMMUNICATION CIRCUIT, by L.A. Ames, et al. October 1961. 67 pp. incl. illus. AFCRL 757   Unclassified report

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3. Scatter Propagation
4. Radio Communication Systems
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